NITROGEN MINERALIZATION AND NON-SYMBIOTIC NITROGEN FIXATION IN AN AGE SEQUENCE OF SLASH PINE PLANTATIONS IN NORTH FLORIDA

BY

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Ammonification, nitrification, and non-symbiotic N_2 fixation were studied in an age sequence of slash pine plantations (0-, 9-, and 29-years-old) in North Florida to determine the effects of burning and of phosphorus and nitrogen fertilization.

Ammonification and nitrification rates were determined by incubating surface soil cores in the field and laboratory. In the laboratory, unsaturated (aerobic) and saturated (anaerobic) cores were incubated at 25° C for 30 days. In the field, cores were enclosed with nylon-mesh bags containing a mixed-bed ion exchange resin to improve gas diffusion and permit moisture content changes during the 30-day *in situ* incubation. Biological N_2 fixation was assessed using the acetylene reduction technique.

Results indicated little differences in ammonification and nitrification rates among plantation ages, except in the 29-year-old plantation site where ammonification was lower in the summer, and in the clearcut site where nitrification was higher in the spring.

Average ammonification and nitrification rates were estimated to be 5-10 and 0.5 mg N/kg-mo, respectively. In general, NH_4-N concentrations were 15 mg/kg and NO_3-N concentrations 2 mg/kg in the cores after the incubation period. Rates and concentrations in the field decreased from summer to spring.

Treatments had a small and temporary effect on the N processes, except in the N-fertilized plot where both ammonification and nitrification were highly stimulated. Potential N_2 fixation rates were 3.0 N/ha-yr and could account for about 10% of the N uptake of the vegetation. Treatments had little effect on fixation, although consistently lower rates occurred in the N-fertilized site. The recent clearcut area showed higher rates, probably related to higher soil surface moisture contents, temperatures and light intensities.

A synthesis of information indicates that N-mineralization is the major source of available inorganic N for vegetation uptake in established stands.

INTRODUCTION

Over 115 million cubic meters of round wood are harvested annually from pine forests of the southeastern U.S. This represents about 45% of the total U.S. softwood fiber production (U.S. Forest Service, 1990). By the year 2030 it is expected that this figure will increase to 175 million cubic meters.

Intensive management practices are and will continue to be required to meet actual and projected demands, particularly if the forested land base decreases in extent. In order to achieve this goal, careful management operations, based on a knowledge of ecosystem processes, are essential to maintain high productivity levels and avoid site deterioration and declines in subsequent harvest returns (Evans, 1976; Pritchett and Morris, 1992).

Forest stands of the lower coastal plain region of the southern U.S. usually grow on very infertile, poorly drained, acidic sandy soils. As such, these stands must depend to a large degree on nutrients coming in the precipitation, those stored in the forest floor and released through mineralization or fires, and on their ability to efficiently utilize and internally recycle nutrients (Miller et al., 1979). In the case of N, additional inputs may come through biological nitrogen fixation such as that by Myrica cerifera L. when present in the understory of these forests (Permar and Fisher, 1982).

Many studies have been performed in Florida to evaluate the effects of harvest methods, site preparation, burning, and fertilization on nutrient budgets, pine survival and growth, water quality, site deterioration, etc. (see, for example, Hollis et al., 1978, Burger, 1979; Rickerk, 1981, Morris, 1981, Coleman et al., 1982, Gholz and Fisher, 1982, and Gholz, Fisher and Pritchett, in press).

Nitrogen and phosphorus are the two most widespread essential soil nutrients limiting productivity of these forests as determined by fertilization trials. Large stem growth responses have occurred after application of either P or N or both to young or semi-mature pine plantations (Ballard and Pritchett, 1975; Fisher and Garbett, 1980, Pritchett and Comerford, 1983, Gholz and Fisher, in press).

Several nitrogen processes have been studied with some detail in Florida. For example, Messer (1978) investigated nitrogen cycles of several southern Florida ecosystems using a mass balance approach. Burger (1979) and Morris (1981) determined the effects of silvicultural practices on N mineralization and nitrification in recent clearcut areas, young pine plantations, and natural second growth stands. Mead (1971) and Boomsma (1979) conducted P and N fertilization experiments to study their effect on soil chemical movement, denitrification, NH_4-N volatilization, and mineralization. Perry (1983) and Gholz, Perry, Cropper, and Hendry (in press) investigated N and P mineralization and immobilization rates in decomposing slash pine needles.

Except for the work of Gholz, Perry, Cropper, and Hendry (in press) and Perry (1983) done using an age sequence of plantations, other studies have not been performed for full rotation periods. In

addition, there is little or no information regarding the potential N contribution of non-symbiotic biological fixation on these sites, and the possible interactions between P fertilization and prescribed burning on these and other nitrogen cycle processes.

Therefore, the general objective of the present investigation was to study the effects of nitrogen and phosphorus fertilization and prescribed burning on some nitrogen cycle processes on an age sequence of slash pine (Pinus elliottii var. elliottii Engelm.) plantations having similar site characteristics and historical management conditions. The sites studied include a recently harvested 29-year-old plantation site, a 9-year-old plantation, and a 29-year-old plantation.

Several hypotheses were formulated:

1) P fertilization will stimulate ammonification, nitrification, and non-symbiotic biological fixation. As suggested by Cole and Hall (1981), N and P cycles should be closely interrelated due the fact that N processes tend to require large quantities of energy, with P in the form of ATP needed. Therefore, a shortage of P will restrict N cycle processes.

2) N fertilization will have a different effect on nitrogen processes. Although N mineralization will be stimulated by reducing C/N ratios and possibly by reducing toxin production (allelochemical) by the vegetation (Lamb, 1980), non-symbiotic biological fixation will be inhibited.

3) Burning will stimulate ammonification, nitrification, and non symbiotic biological fixation. During the fire, release of nutrients accumulated in the forest floor (aspacially P),

increases in pH, and possible degradation of toxins are expected to occur, which in turn will stimulate N processes.

4) Effects of treatments on nitrogen processes will be different depending on plantation age. For example, alder plantations tend to experience more severe shortages of available nutrients (Gholz, Fisher, and Pritchett, in press). These conditions may negatively affect the microbially mediated N processes. In a site that has not been burned for many years, a larger release of accumulated forest floor nutrients is expected to occur after a fire. In addition, Rice and Pancholy (1972) have hypothesized that old stands may produce toxins that will inhibit nitrification. In contrast, younger stands should not be limited in the same manner as the old plantation, although relatively low levels of nutrients still exist (Gholz, Fisher and Pritchett, in press).

In a clearcut area, changes in microclimatic conditions, increases in organic matter in the soil, reduced vegetation nutrient uptake, and other factors created by the disturbance, are expected to have a significant impact on soil N processes (see, for example, Matson and Vitousek, 1981).

LITERATURE REVIEW

Nitrogen Cycle in Forest Ecosystems

Fluxes and Storages

Nitrogen cycling is a very complex process because it includes microbially and chemically mediated transformations, various nitrogen-ion species with different behaviors, and may be interrelated with other nutrient cycles, such as P. Transformations occur mainly between soil and atmospheric storages as weathering processes are usually considered insignificant during rock formation, elevated temperatures tend to volatilize nitrogen (Etherington, 1982).

A global model of the nitrogen cycle is presented in Fig. 1. Except for atmospheric and industrial fixation estimates, the remaining values are a little more than an order of magnitude accurate (Etherington, 1982), because of the relatively high degree of difficulty involved in measuring such storages and fluxes.

The nitrogen cycle is characterized by having a complex soil based component of very small magnitude, and a very large but functionally simple atmospheric component (see Fig. 1). Both storages are naturally interconnected mainly through the microbially mediated processes of biological nitrogen fixation and denitrification.

Nitrogen dynamics and distribution for selected unfertilized ecosystems are summarized in Tables 1 and 2. Total uptake is defined as all the nitrogen absorbed annually by the vegetation and net upteke as the N that stays in the vegetation, not recycled by litterfall,

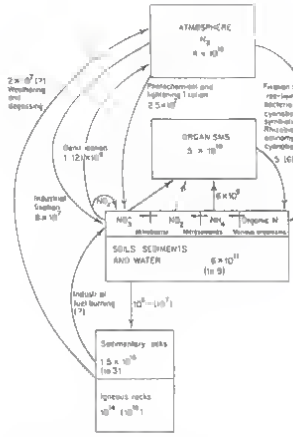


Figure 1 The global nitrogen cycle. Masses (boxes) in tonnes. Fluxes (arrows) in t/yr. Bracket values indicate wide discrepancies in published values (From Etherington, 1982 Copywrite, 1982, John Wiley and Sons, Ltd , reprinted with permission)

Table 1. Nitrogen dynamics in selected unfertilized forest ecosystems (from Keeney, 1980)

System	Uptake		Return		
	Total	Net	Throughfall	Litter	Root-decomposition
	kg N/ha-yr				
Eastern deciduous	79.6	9.0	9.3	54.2	7.1
Eastern deciduous	124.0	14.5	4.4	34.0	70.1
Loblolly pine	69.2	11.1	3.3	27.9	26.9
Loblolly pine	117.1	5.6	0.6	58.2	48.7
Black spruce	--	18.5	--	--	--
Sub-alpine conifarous	23.1	11.9	1.3	16.3	--
Ponderosa pine	--	8.5	--	--	--
Douglas-fir	39.0	23.0	--	--	--
Douglas-fir	--	9-12	--	7-15	--

Table 2. Nitrogen distribution (kg/ha) in some unfertilized forest sites (from Keeney, 1980)

Component	Forest type						
	Eastern deciduous	Eastern deciduous	Loblolly pine	Subalpine coniferous	Douglas fir	Ponderosa pine	Jack pine
	kg/ha						
Trees	361	386	257	372	288	322	172
Roots	181	104	64	--	32	93	18
Forest floor	1100	274	307	650	175	291	391
Soil (0-60 cm)	3600	5080	1763	15855	2809	5200	1100
Sum	5233	5846	2291	16877	3310	5906	1681

throughfall or internal redistribution (increase in biomass N). In Table 3, average nitrogen contents and fluxes are presented for two mature flatwood forests in North Florida. Great variability occurs among and within ecosystems due to differences in climatic and fertility conditions, to stand age, and to varieties in sampling and analytical techniques used.

Cole and Rapp (1981) have attempted to summarize patterns observed in various worldwide temperature forest ecosystems, and concluded that

1) Coniferous forest floors and their nutrients have longer turnover times than deciduous forests.
2) On the average, only 7% of the nitrogen is held in above-ground vegetation storages.
3) Rates of nitrogen uptake and requirements are usually higher in deciduous than coniferous forests.
4) Deciduous forest trees internally retranslocate higher amounts of nitrogen than coniferous forests.
5) In coniferous forests, uptake and requirements of nitrogen strongly correlate with biomass production.
6) Coniferous species are more efficient than deciduous species in producing biomass with the same amount of nitrogen uptake.
7) Efficiency of production/unit nitrogen uptake increases as nitrogen becomes limiting.
8) In general, more nitrogen is added to forest ecosystem than is lost.

Table 3. Average nitrogen storages and fluxes for two flatwood forests in North Florida (from Fritchett and Morris, 1982)

Components	N
	kg/ha
Reserves	
Foliage and branches	44.0
Bolewood with bark	66.0
Understory veg.	30.0
Forest floor	271.0
Mineral soil (1 m)	2959.0
Total	3370.0
	kg/ha
Inputs	
Atmospheric	5.6
N fixation	2.4
Outputs	
Leaching	0.1
Erosion/runoff	1.9
Denitrification	0.6

In the southeastern U.S., Switzer and Nelson (1972) investigated nitrogen accumulation and cycling in loblolly pine (Pinus taeda L.) plantations in North Carolina during the first 20 years of development. Among their findings were that the amount of N in the system increased about 4 times when compared with initial nutrient storage, that a sizeable portion (about 39%) of the annual requirements was met by internal transfer, and that N tended to accumulate in the tree biomass and forest floor over time. They also concluded that the relative supply of N from the soil mineral and organic sources may be low compared with the tree requirements, but biomass production was not yet inhibited due to the increasing redistribution of N within the trees. They suggested that one explanation for the relatively long-term observed response to fertilization in these stands, especially to P, was this ability of the stands to recycle nutrients internally.

A similar approach was used by Gholz and Fisher (1982) and Gholz, Fisher, and Pritchett (in press) when they investigated an age sequence of slash pine plantations in Florida. In these studies, changes in storages and fluxes of N and other nutrients were monitored in stands ranging from 2- to 34-years-old. Their conclusions included the following:

1) Maximum N uptake occurred between 8 and 14 years.
2) Very high N uptake rates were observed even in 2-year-old stands due to an active understory, with rates increasing less than 50% to the maximum at 8-14 years.
3) Internal redistribution (trees and understory) increased greatly as the stands got older, due to the increasing dominance by pine.

4) N and P use efficiencies (net primary production:uptake) increased with time and were very high in the older plantations.

5) N and P concentrations in tree components, including coarse roots, declined over time.

6) Decreased nutrient availability, especially of P, explained why there was a cessation in vegetative biomass increments when these plantations reached 25 to 30 years.

In another experiment performed in the same age sequence of plantations, Gholz, Perry, Cropper, and Hendry (in press) found that fresh needle litter contained very low initial levels of N and P, and that total needle N contents tended to remain constant and P contents to increase for over 24 months, indicating that N and P were strongly immobilized.

On these sites, with a highly weathered sandy soil and low ion exchange capacity, most of the nutrient retention and transfer are associated with the forest floor and the A horizon. It is not surprising, then, to observe positive results when N and/or P, alone or in combination with other nutrients, are added to the sites. Under non-fertilized conditions, pines may cope with poor nutrient availability by having slower growth rates to reduce requirements (Chapin, 1983) or by accumulating essential nutrients in biomass components and maintaining "tight" internal cycles (Miller et al., 1979). In addition, special mechanisms or associations have evolved to enable trees to obtain otherwise unavailable nutrients (e.g., mycorrhizae for P uptake) or to inhibit certain microbial processes that may increase losses of nutrients (e.g. nitrification and allelochemicals (Rice and Pancholy, 1972).

Nitrogen Mineralization and Immobilization

Mineralization is the process whereby complex organic (detrital) compounds are converted by microorganisms to inorganic compounds which can be reutilized by microorganisms or released to the environment. Nitrogen mineralization can specifically be called 'ammonification' as proteins, amino acids, amino sugars, etc., are degraded to ammonium-N.

Nitrogen mineralization and immobilization rates are very important parameters to consider in order to assess the N status of forest ecosystems as nitrogen availability for plants is regulated through these processes. In addition, they can be used as a measurement of the quality and quantity of organic matter substrate present in the site (Burger, 1979), and as an estimate of the proportion of the total nitrogen pool that may be utilized by the ecosystem (see Stanford and Smith, 1972).

Several interacting factors affect mineralization rates. Among the most important ones are the quantity of potentially mineralizable organic N, availability of utilizable carbon sources, C/N ratios, temperature, pH, moisture, and the presence of other potentially limiting nutrients such as P.

In addition to the above factors, Anderson et al. (1981), and others, have indicated that the presence of saprophitic grazers may significantly accelerate release of N immobilized in bacteria and fungi (see also Witcamp, 1971). Bacteria and fungi tend to strongly complete for ammonium-N (Winsor and Pollard, 1956), so that by reducing their population size, ammonium-N may be available to plants. In sites where such grazers are not abundant, drying and wetting

cycles may increase availability of N by reducing bacterial and fungal populations (Birch, 1958; Sehrawat, 1980; Morris, 1981).

Carbon/nitrogen ratios have been frequently used as a mineralization-immobilization index. Higher ratios will induce immobilization. Forest floors C/N ratios vary from 40 to over 60 corresponding to total N concentrations of 0.5-1.4% in an ash-free basis (Keeney, 1980). For bacteria, C/N ratios range from 5-15, and are slightly higher in fungi (Messer, 1978). As a consequence, during initial decomposition of organic matter, immobilization will prevail until C/N ratios are reduced to about 20-25.

Although C/N ratios give some idea of the rates of mineralization, other factors must be considered. Herlihy (1979) found that higher mineralization rates tended to occur when labile organic matter was present, and Boomsma (1979) observed an increase in mineralization when soluble organic carbon increased in the soil. On the other hand, Youngberg (1978) concluded that N immobilization was partially related to total N content of the forest organic materials. In addition, Greenland (1958) mentioned that toxins related from savanne grass roots inhibited mineralization, and Alexander (1977) stated that the presence of lignins in the organic matter disrupt enzymatic processes of microorganisms which degrade proteins. These last factors may explain why pine needles tended to immobilize N (Jones and Richards, 1977).

The examples above provide some basis for concluding that C/N ratios may poorly correlate with mineralization rates. Total carbon and nitrogen analyses do not give a complete idea of the complexity of the organic materials and do not indicate the degree of toxicity or

availability of energy sources for microorganisms present in the organic matter

In general, increasing moisture content to field capacity and increasing temperature of the soil will also tend to accelerate mineralization (e.g. Matson and Vitousek, 1981). As mentioned before, wetting and drying cycles may also favor the release of N. Herlihy (1979) also found that low mineralization rates occurred in sandy soils when compared with clayey soils. He suggested that such a trend may be due to poor moisture retention capacity of the sandy soils which inhibits the growth of microbial populations. Finally, Cameron and Posner (1979) found a strong interaction between moisture content and C/N ratios. mineralization was higher under waterlogged conditions only when C/N ratios were high, but no differences were observed when C/N ratios were low.

Mineralization rates may also vary with stand age and dominant species in an ecosystem. Robertson and Vitousek (1981) noted that N mineralization in a soil from a primary sere increased initially but leveled off with time, while in soil from a secondary sere it remained relatively constant. Highest rates were observed in the oldest secondary sere. Perry (1983) and Ghalz, Perry, Cropper and Hendry (in press) found no significant differences in decomposition when slash pine needles from an age sequence of plantations were studied after decomposing in the field for one year. But after 24 months, decomposition and P mineralization rates tended to decrease in the needles coming from the oldest plantations. Less, but highly significant, N immobilization was observed with no effect of stand age. On the other hand, Jones and Richards (1977) found that when

pine needles from a 29-year-old slash pine plantation were added to incubating soil, heterotrophic bacteria and fungi were stimulated to immobilize ammonium-N. Berg and Ekbohm (1983) determined that decomposing Scots pine (Pinus sylvestris L.) needles also tended to immobilize N, but only when initial N concentrations in the needles were low. Such accumulation lasted up to 2 years to when approximately 60% of the mass was lost.

Fogel (1980) observed that in sites where species associated with ectomycorrhizal fungi predominate, raw humus, very difficult to decompose, accumulated. Singer and da Silva (1979) suggested that such a phenomenon may be due to the ability of mycorrhizae to absorb essential mineral nutrients from the litter, to the ability of mycorrhizae to absorb essential mineral nutrients from the litter, to the ability of mycorrhizae to rapidly utilize easily available C substrates, and/or to the ability of these fungi to produce antibiotics. All these conditions would tend to reduce N mineralization.

Forest management practices may also have an effect on mineralization rates. According to Burger (1979) and Morris (1991), mineralization rates increased with intensity of site preparation, but potentially mineralizable N was significantly reduced and was almost completely depleted at the end of two years in the most intensively prepared sites (including chopping, burning, discing, and bedding). Such changes in N mineralization patterns may be related to changes in temperature, moisture content, and availability of nutrients and organic carbon in the soil.

Fertilizer applications may have different effects on this process. Overrein (1967) observed that addition of inorganic NH_4-N or

NO_3-N stimulated N release from organic matter (a phenomenon he termed "priming effect"), but that little effect was observed when urea was applied. On the other hand, Doomsma (1979) stated that additions of urea, and to a lesser extent, ammonium sulfate, stimulated release of organically bound N, mainly due to an increase in soluble organic carbon after fertilization.

Prescribed burning may have a similar stimulatory effect, as fire tends to increase nutrient contents and pH in the soil, tends to decrease C/N ratios, and maybe degrade toxins stored in the forest floor (see review by Ralson, 1979). In some pine plantations in Florida, Burger (1979) found that such changes were very temporary, but were still sufficient to significantly change the N fluxes and pools of the site.

Nitrification

Nitrification, or the oxidation of ammonium to nitrate, is basically restricted to autotrophic bacteria, mainly Nitrosomonas and Nitrobacter. During this reaction, energy is released to assimilate CO_2.

Fotch and Verstraete (1977) indicated that soil pH, moisture content, oxygen supply, and temperature are the most important parameters controlling nitrification when sufficient substrate is available. They found that optimum nitrification rates occur in neutral or slightly alkaline pH, with moderate moisture contents and at a temperature between 20° and 30° C.

But these factors interact in various ways, so nitrification has been observed to occur in a great range of conditions. For example, Kowalenko and Cameron (1976), during an incubation experiment on a

clay loam soil, established that a strong interrelation between moisture content and temperature existed. Sahrawat (1982), working with some tropical soils, found no correlation between organic carbon or total N contents in the soil and nitrification rates. Instead, a strong relationship was found between N mineralized and nitrification (see also Robertson and Vitousek, 1981). When availability of ammonium-N is low, nitrification will decrease (Verstraete, 1981, Adams and Attiwill, 1982) mainly because heterotrophic bacteria are considered to be better competitors than nitrifiers for N sources (Jones and Richards, 1977, Verstraete, 1981).

Sahrawat (1982) also found that pH was only correlated with nitrification when values were below 6.0; a negative relationship was observed when acidity increased. In alkaline conditions, no significant differences were detected with changes in pH. Because of the powerful effect of low pH's on nitrifiers, acid forest floors and soils are expected to have very low populations of such bacteria (Smith and Pritchett, 1976, Keeney, 1980). But Burger (1979) indicated that for some slash and loblolly forests in Florida, nitrification proceeded even at pH's around 4.5, a unit lower than what is usually reported for agricultural soils. In addition, Walker and Wickramasinghe (1979), working with acid tea soils in Sri-Lanka, observed that nitrification occurred at pH's as low as 4.1. These results suggest that specialized bacteria may evolve in certain environmental conditions.

Ecological succession may also influence nitrification, but still a lot of controversy exists in the literature. According to Rice and Pancholy (1972), mature forests tend to produce allelochemicals that

reduce activity of nitrifiers. In this scenerio, N will be conserved as nitrate-N would be rapidly lost through leaching or denitrification. In addition, vegetation which tends to preferentially absorb nitrate, as appears to be the case in early successional stages, will be outcompeted.

Much controversy surrounds this hypothesis, as various investigations report opposing results. For example, Lamb (1980) found no decrease in nitrification with succession in several forests in Australia. He concluded that nitrifier activity was related to N availability of the site rather than as an evolutionary strategy (see also Verstraete, 1981, Adams and Attiwill, 1982). Robertson and Vitousek (1981) also were not able to observe nitrification decreases with successional stage, and Robertson (1984) found increases in nitrification through the early successional stages of a low land ecosystem in Costa Rica instead, with a leveling off later. He also observed that ammonium availability along the sere regulated the rate of nitrification, and that in soils of all sites most of the ammonium was transformed to nitrate. Greenland (1958), on the other hand, suggested that even grasses in a tropical savanna may release toxins that will suppress nitrifier activity. Other investigations may be cited, but the ones mentioned above are indicative of the debate surrounding this topic.

As with organic N mineralization, ecosystem disturbance may lead to changes in nitrification rates. Recently, Vitousek and Melillo (1979), Matson and Vitousek (1981), Vitousek et al. (1982), and others, have reviewed and discussed in detail the patterns of nitrification and nitrate mobility for more than 17 different forest

types after disturbence. In a majority of the cases, nitrate accumulated in the sites, suggesting increases in nitrification activity. Such effects were attributed to increases in ammonium availability, through increases in mineralization rates, to reductions of competition for substrate, to degredation of potential toxins, to improvement of substrate quality, and/or to direct changes in environmental conditions such as moisture content, pH, temperature, etc

Nitrogen additions may favor nitrification, as was observed by Otchere-Boateng and Bellerd (1978) in fertilization trials in secondary forests in the Pacific Northwest, and Boomsma (1975) in a 23-year-old slash pine plantation in North Florida, although in this last case the effect was not very strong. Robertson (1984) also observed a dramatic stimulation of nitrification when NH_4Cl was added to some tropical forests, with the stimulus attributed to increases in ammonium substrate, organic water soluble carbon, and pH. Burger (1979) found an increase in nitrification after prescribed burning which may be the result of the increase of these factors after the fire.

P fertilization has also been cited as having a stimulating effect on this nitrogen process (see review by Cole and Heil, 1981), although information on the subject is relatively scarce.

Denitrification

Denitrification is defined as those reductive reactions which produce nitric oxide (NO), nitrous oxide (N_2O) and dinitrogen (N_2) gasses (Knowles, 1981) Usually such activity is associated with denitrifier bacteria which utilize nitrate as an electron acceptor

when oxygen concentrations are low. But in addition, Blackmer and Bremner (1979) discovered that some of these gasses may also be produced during autotrophic nitrification reactions.

In general, two types of denitrification processes have been distinguished: the biological and the chemical processes (Knowles, 1982). Biological denitrification has been the more studied and is considered to be the most significant contributor of N losses from ecosystems.

Environmental requirements for optimum biological denitrification rates have been extensively reviewed by Fotch and Verstraete (1977), Knowles (1981, 1982), and Firestone (1982), although the majority deal with agricultural systems. Among the most important factors favoring denitrification are: low soil oxygen concentrations, neutral to slightly alkaline pH's, relatively high availability of C and NO_3-N, and temperatures around 35° C. In addition, denitrification tends to be higher with wetting and drying cycles, and in soils with high clay content. Plants also may exert a strong influence on this process (Firestone, 1982) by supplying carbon rich exudates, and by reducing oxygen concentrations in the rhizosphere. On the other hand, plants may reduce denitrification by competing for N substrates, especially in sites low in N (Smith and Tiedje, 1979).

Under acidic soil conditions denitrification decreases rapidly. Two major explanations have been proposed. One is that nitrate may be used in the assimilatory reduction to ammonium (Bremner and Shaw, 1958; Knowles 1981, 1982), decreasing availability of substrate, and the second is that molybdenum, a necessary element in the enzymatic

system of denitrifiers, may become limiting under this condition (Firestone, 1982).

Although low pH's tend to inhibit denitrification, Wickramasinghe and Tallbudeen (1981) found that in some tropical soils, evolution of nitrous oxide and dinitrogen gasses was occurring even at a pH of 4.0 when soil was amended with glucose. This suggests, as in the case of nitrifiers, that certain denitrifier bacteria may be adapted to special environmental conditions, although under these low pH's, chemical denitrification may be occurring (Nelson and Bremner, 1969; Nelson, 1982).

In general, forest soils have been considered to have low biological denitrification rates not only because of the generally acidic conditions but also because of the low substrate availability (Keeney, 1980). Nonetheless, Todd et al. (1978) found, in an extreme example, that potential denitrification in some deciduous forests may be high and may exceed stream N losses by as much as 200 times. In this study, highest rates occurred in the leaf and wood litter, but the largest total amounts occurred in the soil. Of the estimated 18.2 kg N/ha-yr denitrified, 80.5% was lost from the soil.

In a sugarcane plantation grown on a South Florida Histosol, Messer (1979) detected high gaseous losses of N. He determined average rates of 250 Kg N/ha-yr with peaks following rainstorm events. On this site, high rates would be expected because of large amounts of available C and probably also N. For other agricultural areas, N losses through this process have been estimated to be between 0 to 70%, with a mean of 25 to 30%, (Firestone, 1982). This suggests that in certain situations, losses may be considerable.

On the other hand, Boomsma (1979), working with a slash pine plantation fertilized with several nitrogen sources, observed that denitrification losses accounted for only 1 to 2% of the N fertilizer applied. The percentage values obtained varied depending on the N_2/N_2O ratio assumed in the calculations of his results and on the type of fertilizer and rate of application. In addition, he pointed out, as in Messer's study, that denitrification occurred in pulses following rainstorms, and that increases in available C after fertilization, especially urea, stimulated this process.

Other management practices besides fertilization may also alter activity of denitrifiers. In plantations in Florida, harvesting, chopping, burning, etc. may increase pH, moisture content, and substrate, and C availability in soils (see Burger, 1979; Morris, 1981), all of which will tend to favor denitrification. Unfortunately no study on the possible denitrification rates in these disturbed sites is available.

Nitrogen Volatilization

Besides denitrification, other processes may release gaseous N products in the environment (Nelson, 1982). For example, burning may volatilize 25 to 60% of the total N found in the forest litter depending on fire temperature and N content of the organic material (see review by Raison, 1979). During site preparation, burning is used, among other techniques, to remove slash and other organic debris. According to Pritchett and Morris (1982), N volatilization losses after this operation was performed in some sites in Florida ranged from 40 to 100 kg/ha (see also, Burger, 1979, and Morris, 1981). In a tropical ecosystem, Ewel et al. (1981) estimated N

volatilization losses of 480 kg/ha, or 23% of the total N pool, when the site was slashed and burned. But in general, N outputs due to fires are low due to incomplete burning of organic debris, low temperatures, and low penetration of flames in litter layer (Raison, 1979).

Ammonia volatilization from other processes may also contribute to N outputs. High rates have been observed in alkaline soils dominated by sands, especially when drastic changes in temperature and moisture occur and when N fertilizers have been applied (Nelson, 1982, Stevenson, 1982). Effects of plants also must be considered, as they may decrease volatilization by decreasing availability of NH_4-N in the soil, or may be sources of NH_3 as was observed by Farquhar et al (1979) in senescing leaves of an agricultural plant. Additional reduction in N gaseous losses to the ecosystem by the vegetation may occur. According to Denmead et al. (1976) some plant canopies have the ability to absorb gaseous N products, although its importance to the ecosystem is unknown.

In unfertilized forest soils, ammonia volatilization losses are insignificant (Keeney, 1980), although in fertilized forest soils such losses may vary from less than 5% (Volk, 1970) to as much as 40% (Nommik, 1973). Baomsma (1979) found that less than 3% of the N applied was lost through volatilization. According to Marshall and Debell (1980) much of the variation observed between and within investigations is related to the specific site conditions, especially pH and rate and type of fertilizer, but also to the different methodologies used and to the specific time the measurements were

taken. For example, volatilization losses are lowest after rainstorm events

Biological Nitrogen Fixation

According to Postgate (1974), biological nitrogen fixation accounts for at least 90% of the terrestrial N turnover in the global N cycle. Most of the N used or stored in an ecosystem has originated through this process, as very few parent material are rich enough in N to supply these observed amounts through weathering. Paul (1978) estimated that biological fixation annually contributes 5-10% of the nitrogen circulating between vegetation and soil components, although percentages may be higher in N-poor environments

Nitrogen fixation has been demonstrated only for prokaryotic organisms, either bacteria or blue-green algae (Postgate, 1974). Bacterial nitrogen fixers range from obligate aerobes to anaerobes, and from free-living to symbiotically associated ones. Some bacteria also have photosynthetic capabilities.

Most favorable conditions for fixation rates include large amounts of available energy sources, relatively low oxygen concentrations, moderate to high moisture contents, temperatures between 20° and 30° C, and neutral pH's. For symbiotic relationships, additional factors which affect plant photosynthate production must also be considered. In addition, availability of Mo, Fe, and P, and low levels of N, especially NO_3-N, favor biological fixation (for detailed discussions, see reviews by Child, 1981, Granhall, 1981, and Havelka et al., 1982).

Although thermodynamically the overall reduction of N_2 to NH_4-N is exothermic, releasing about 9 kcal/mol (Child, 1981), large amounts

of energy are necessary to break the N_2 triple bond. From 25 to 28 molecules of ATP/molecule of N_2 are utilized. This represents about 4 kg of carbohydrates/kg of N fixed (Havelka et al., 1982).

The largest contribution to biological fixation is from the bacteria of the genus Rhizobium in association with leguminous species, although other associations are important, such as the one present in species like Alnus. Due to the symbiotic relationship, fixation efficiency is greater than with asymbiotic organisms. For Rhizobium, the efficiency rate has been calculated to be between 0.15 to 0.25 g N fixed/g of C used, while in the case of Azotobacter, the rate is only about 0.01-0.02 g N fixed/g C (Stewart, 1975; Fata and Harridge, 1978).

Average fixation rates for forest ecosystems are about 10 kg N/ha-yr (Burns and Hardy, 1975; Cole and Rapp, 1981), varying from as little as 1-2 kg/ha-yr for free-living association, to over 200 kg/ha-yr for some symbiotic relationships.

For coniferous forests, rates of fixation have been considered to be low (Jonas et al. 1974, Jones, 1979) but amounts fixed may represent a significant portion of the vegetation N requirements. For example, Ovington (1954, 1957) estimated that Douglas-fir (Pseudotsuga menziesii Mirb.) annual N requirements ranged from 17-38 kg/ha, of which 8-25 kg/ha was supplied by biological fixation. Granhall and Lindberg (1978) determined that N fixation varied from 0.3 to 38 kg/ha-yr for spruce (Picea ables (L.) Karst.) and Scots pine (Pinus sillvestris L.) forests in Norway. Richards (1964), and Richards and Bevega (1967) estimated rates as high as 50 kg N/ha-yr for an ionemture coniferous forest. For deciduous forests, Todd et al. (1975)

calculated rates of about 11 kg N/ha-yr, with highest values observed in leaf and wood litter components. These works suggest that generalizations are difficult due to the huge variability between the sites, species, and techniques used in the measurements.

Some studies to determine the fate of the N fixed products, in the case of non-symbiotic relationships, have been performed. Richards (1973) indicated that the nitrogen fixed was rapidly absorbed by the plants, especially those associated with mycorrhizae. Jones et al. (1974) and Jones (1978) also found that losses of biologically fixed N were low when Douglas-fir and larch (Larix eurolepis A. Henry) seedlings were studied, although some denitrification occurred. They also observed that most of the products were absorbed directly by the roots, but others required to be mineralized.

Phyllosphere N fixation may also constitute an important source of N for ecosystems. According to Ruinen (1961), N fixed by free-living bacteria in leaves from some tropical successional species, may help replenish N pools of the site after it is left in fallow period. For some temperate ecosystems, Todd et al. (1978) estimated rates of only 0.25 kg N/ha-yr for an oak-hickory forest, while the soil component reached a value of 8.5 kg/ha-yr. On the other hand, Ovington (1954, 1957), Jones (1970), and Jones et al. (1974) calculated rates of 14-20 kg/ha-yr in Douglas-fir canopies. The higher rates observed in coniferous forests when compared to deciduous forests, has been attributed to the longer leaf retention which permits the establishment of the nitrogen fixers. However, other factors are involved as Granhall and Lindberg (1978) found only insignificant rates in the coniferous forests they studied.

Wood debris and litter may be potential sites for biological N fixation, as both of them are rich in energy sources and contain low levels of N (Aho et al., 1974). Corneby and Waide (1973) estimated an annual input of 0.9 kg N/ha-yr in decomposing chestnut (Castanea sp.) logs. This represented about 4% of the total N of the ecosystem. Larsen et al. (1978) found similar rates (0.7 kg N fixed/ha-yr) in western Montana wood debris. Rates varied depending on decay stage, tree species wood, and type of fungi present. O'Connell et al (1979) determined rates as high as 14.3 g N/ha-day when they sampled the litter layer of eucalyptus forests in south-western Australia. They suggested that this result helps explain in part the N concentration increases observed over time in the litter layer. Finally, Silvester and Bennett (1972) detected significant fixation activity in forest floors of several coniferous stands in New Zealand, especially in the humus and fermentation layers.

Fixation rates also have been associated with the rhizosphere of conifers. For example, Silvester and Bennett (1972) found high activities near or within the root system of coniferous trees. They even discovered that some roots contained modified mycorrhizal short prolongations which apparently hosted nitrogen fixers. When they washed these roots, 50% of the activity disappeared suggesting that they are externally associated. Richards (1973) also determined that the rhizosphere of coniferous trees, such as slash pine, strongly stimulated fixation, although he did not observe any sort of root specialization. Both aerobic and anaerobic bacteria were isolated from these roots, but apparently only the anaerobes were able to

utilize the root exudates. Efficiency of fixation is lower in anaerobic bacteria (Hill, 1978).

Not all root environments are able to support nitrogen fixers. Jones (1978) found no strong activity in root systems of Douglas-fir trees, and Shriedhara and Negedra (1977) concluded that certain Arlstida species produced allelochemicals that reduced fixation and prevented nodulation in legumes.

The ecological significance of biological nitrogen fixation is most evident in pioneer and early successional stages of a site. In primary seres, organisms such as blue-green algae and lichens have a substantial colonization advantage over other organisms as they are relatively independent of substrate N status (Etherington, 1982). In secondary succession, especially in the early stages, plant species associated with nitrogen fixers tend to dominate the site as the demand for N sources through competition increases (Garham et al., 1979, Etherington, 1982). Once N levels are high, or P becomes limiting, the energy costs of maintaining the symbiotic fixers may become a great disadvantage when compared with non-fixing plant species. This is evident in mature ecosystems where heterotrophic nitrogen fixers predominate over the symbiotically associated species (Granhall, 1981). An analogous situation occurs with species associated with mycorrhizae (see Janos, 1980a, b). When nutrients are limiting, species associated with mycorrhizae dominate the ecosystem, but when nutrient availability is high or extremely low, the reverse occurs.

As expected, N-fixing efficiency decreases substantially in non-symbiotic relationships. In early successional or disturbed

sites, values of 30 kg/ha-yr or more have been recorded, while average values between 0.5 and 10 kg/ha-yr were observed in undisturbed or mature ecosystems (Stewart, 1978; Etherington, 1982). These high rates associated with the disturbed areas may be an important mechanism to reduce N stress, as much of the N pools of the ecosystem may have been lost after the disturbance (see Vitousek and Melillo, 1979).

Finally, nitrogen fixers have an important role in aiding decomposition of organic matter in the soil, especially in those substrates having high C/N ratios by increasing N content of the material. Bacteria with N fixation capabilities and other heterotrophic bacteria would tend to colonize these sites as they become less selective for C sources, although in some substrates high in lignin content, fungi will tend to be present, too (Granhall, 1981). After C/N ratios decrease, other types of organisms can invade such habitats (Baines and Millbank, 1978; Granhall, 1981) Nitrogen fixers are also symbiotically associated with wood-boring insects, such as termites and pine bark beetles, which apparently aid in the digestion of the wood ingested (Benemann, 1973; Bridges, 1981).

Management practices may affect N fixation rates. For example, because heterotrophic fixers are strongly dependent on external energy sources, vegetation and slash removal during site preparation may drastically reduce fixation rates (Granhall and Lindberg, 1978), but may be enhanced in windrows or slash piles. On the other hand, application of N fertilizers, especially those containing nitrate, will decrease nitrogen fixation activity (Spiff and Odu, 1972; Havelka et al., 1982) but, the addition of other nutrients, such as P or Mo,

may have opposite results (Ludgran, 1978, Granhall, 1981) In addition, prescribed burning will tend to stimulate nitrogen fixation, not only because nutrients are released, but also because pH tends to increase, carbon sources may become more available, and toxins detrimental to nitrifier bacteria may be eliminated. Jorgansen and Wells (1971) observed higher fixation activity after a loblolly pine (Pinus taeda L.) forest was burned; rates reached values of 23 kg N/ha-yr, although spatial variability was very high. Other examples of affects of fires on this nitrogen process have been reviewed by Ralson (1975).

Nitrogen Transport In Soils

An understanding of N movement in soils is important for two main reasons. First, significant losses of N, especially nitrate, may occur through leaching, and second, N reaches the root absorption zone primarily through mass transport.

Most studies and models dealing with N movement in soils have been performed in or for agricultural systems. Rao et al. (1976) described a simulation model which accounts for microbial transformations, ion exchange processes, and transport of the various N ionic species. Davidson and Rao (1978) evaluated some simple models of N movement in soils which also consider physical, biological and chemical aspects. Misra et al (1974) also presented several models and equations to describe leaching processes in soils. Recently, Nielsen et al. (1982) reviewed this topic discussing deterministic and stochastic models, as well as problems associated with spatial variability and sampling procedures.

For steady state conditions, one-dimensional N movement in soils may be described by using the following equation (Rao, pers. comm., 1982; Starr, 1983):

$$wdC/dt + bdA/dt = wD_h d^2C/dx^2 - qdC/dx +/- S \qquad (1)$$

where

d = partial derivation

w = volumentric water content

t = time

b = bulk density

A = N concentration in the absorbed phase, non- or linearly dependent on C

D_h = total dispersion coefficient = to the sum of effective molecular diffusion, + mechanical dispersion, + dispersion caused by diffusive solute transfers between stagnant and mobile water around soil particles

x = distance

q = Darcy's water flow

S = sinks and sources.

Several factors are considered to be constant through time (e.g., w, b, q, and D_h) and N transformations are assumed to follow Mechaelis-Menten zero or first-order kinetics. The above equation (1) indicates that movement of N in the soil may be very complicated as many parameters must be studied simultaneously. Complexity will also increase if some of the assumptions do not hold, and if spatial variability, due to chemical or physical aspects, is high.

Nitrogen losses through leaching vary depending on the N species. Usually ammonium-N is not easily leached out from soils having high cation exchange capacities. In addition, in clayey dominated soils with 2:1 layer silicates, ammonium-N leaching may be reduced not only because of electrostatitic attraction to the soil particle, but because it may be strongly fixed or trapped in the lattice structure (see review by Nommik and Vahtras, 1982). Such ammonium-N will become less accessible for nitrification and volatilization losses (Kudeyarov, 1981). In the case of nitrate, losses are generally high, except in acidic soils containing high quantities of amorphous materials, where absorption may be significant (Kinjo and Pratt, 1971).

Sandy soils have low ionic exchange capacities (mostly depending on organic matter content and pH) and do not contain any amorphous materials to retain and reduce N losses through leaching. Nonetheless, Morris (1981) found that even after intensive management practices, N leaching, detected by lysimetry, was minimal in a flatwood soil. Also Riekerk et al. (1980) and Riekerk (1981, 1982) reached a similar conclusion when they analyzed runoff water concentrations from the same watersheds. This suggests that some other mechanisms of retention may exist in this area, such as immobilization in the organic matter (see Vitousek et al., 1982), or that some of the N was lost through denitrification. Also such results may be related to the low fertility of the area so that when the sites were disturbed, availability of nutrients did not increase significantly.

In other sites, results have been different. For example, McColl (1978) found significant increases in N and other nutrient concentrations in soil solution samples after an eucalyptus plantation in California was clearcut. Also, Hollis et al. (1978) detected larger N leaves in runoff water after a flatwood forest in northwest Florida was harvested to establish a pine plantation. Levels decreased rapidly, and returned to control conditions a short period after the disturbance.

Application of nitrogen fertilizers to sandy soils will rapidly increase soil solution concentrations of this chemical and as a consequence, potential leaching losses is expected to increase. Although no direct measurements were performed, Boomsma (1979) suggested that an elevated portion of the applied fertilizer may have been lost through this process. He also suggested that when urea-N was applied, leaching losses may have been relatively lower because the fertilizer tended to increase pH which in turn may have helped increase the cation exchange capacity of the soil (see also Otchere-Boateng and Ballard, 1978).

The amount of N leached will vary from site to site depending, among other things, on degree of disturbance, rainfall patterns, soil type, rates of plant uptake, nutrient status of the soil, etc. Vitousek and Melillo (1979) recently reviewed and discussed some of the patterns and mechanisms of N losses observed in disturbed forest ecosystems.

Finally, it is important to mention that macropores and soil particle aggregation may play a significant role in N movement in soils, especially in clayey soils. Under unsaturated conditions, soil

solution will move through relatively small pores inside aggregates tending to help storage of nutrients but when soil saturates, solution will rapidly move through macropores (see Bouma, 1981). In this last case, potential losses of available nutrients may be greater. In sandy soils, where aggregation is usually poor, chemical rather than physical properties, such as water repelency, may influence water and solute movement (Bond, 1964).

Nitrogen Uptake by Plants

Nitrogen will reach plant roots mainly by mass flow, that is, the convective flow of the solution to the roots as a result of plant transpiration (Barber, 1981). According to Barber and Olson (1968), almost 100% of the N absorbed by corn is supplied by this process, although in species associated with nitrogen fixers this proportion is decreased.

Several models for N transport to roots have been developed, mainly for agricultural conditions. One of such models was proposed by Claassen and Barber (1976), and includes 10 basic parameters: 3 describing the relationship between net plant nutrient influxes and nutrient concentrations in the soil solution, 3 describing the effect of root surface sizes and increases over time, 3 describing the rate of nutrient supply to roots from the soil, and the last one describing the rate of water absorption (see also Barber, 1981). Two other models frequently used in the literature are those proposed by Nolz and Ramson (1970) and Nimah and Hanks (1973), but in general, they are relatively complex models difficult to handle in practical situations. A simpler model was described by Davidson and Rao (1978), but the

number of assumptions increases. Further discussions on solute transport to the root area are contained in Nye and Tinker (1977).

Once N reaches the rhizosphere, several factors will affect its absorption. Assuming adequate N availability, plant uptake is influenced by root systems size and rate of absorption/cm² of root (Barber, 1981). In addition, uptake may be significantly enhanced by mycorrhizae not only because of increased surface area, but also because mycorrhizae have the capability to extract relatively unavailable N sources form the soil, can accelerate absorption rates, and can effectively compete with other microorganisms for N substrates (Bowen and Smith, 1981). Also Malajczuk et al. (1981) discovered that mycorrhizae of overstory vegetation may be directly interconnected with nitrogen fixing plants in the understory. By such connection, the authors suggested that N nutrition of the overstory vegetation may be significantly improved.

Transport of N ions from the root to the shoot will not be discussed here. Kirby (1981) reviewed this subject as well as the assimilation and metabolism of the different N species by the plant, and the effect of N on growth.

In mature temperature forests, ammonium-N tends to predominate in soil solutions (Vlassek, 1970, Rapp et al., 1979, Keeney, 1980, Cole, 1981) suggesting that forest vegetation may obtain N mainly as ammonium-N. Rice and Pancholy (1972) claimed that the absorption of such N species is very advantageous as it may be incorporated directly as amino acids. In contrast, if nitrate-N is absorbed, this must be transformed with the expenditure of high amounts of energy. But its predominance in the soil solution may not provide sufficient

justification for concluding that ammonium-N is the preferentially absorbed N species. For example, Petterson (1981) indicated that in most tree species, ammonium-N uptake occurs best in neutral pH, but absorption decreases rapidly in acidic conditions, such as those found in many forest sites. This suggests that maybe the abundance observed is related to lower absolute uptake rates. Other interesting considerations in relation with this topic, were presented by Petterson.

On the other hand, there is some evidence that the form of N absorbed by plants may vary with successional stage. Haines (1977) observed shift from nitrate to ammonium-N uptake in an old field to a Pinus-Quercus successional sere in South Carolina. Chandler (1981) also suggested that early successional species in a tropical ecosystem tended to absorb only nitrate-N. In his experiments with Syzygium floribundum, a species characteristic of mature ecosystems, and Solanum mauritianum, a pioneer species, he showed that Syzygium sp. grew better in soils containing ammonium-N, while the contrary occurred with the pioneer species. These results must be considered in fertilization trials, as type of fertilizer used may stimulate growth of different species.

In addition to N uptake through roots, some investigators, such as Jones (1978) and Freeney et al. (1981), have indicated that some species, including conifers, may obtain N through leaves. But the significance of this process in relation to the overall N requirement of the plant is not well known.

Nitrogen requirements vary depending on site fertility, growth stage, species, and other factors. Ingestad (1979) suggested that N

status of seedlings may strongly affect and may be used to predict N requirements of the plant in the future.

According to the review by Cole and Rapp (1981), temperate conifouers forest requirements for N ranged from 34 to 84 kg/ha-yr, while deciduous forests, on the average, need more N. This may be partly related to greater leaf retention by the conifers, slower growth rates, and higher internal recycling. For coniferous forests, Cole and Rapp estimated that for each kilogram of N absorbed, about 184 kg/ha of above-ground biomass was produced annually.

N-P Interactions

Little information exists on the possible interactions between N and P cycles, although some concepts were reviewed by Cole and Heil (1981).

N and P cycles are expected to be closely associated because of the high energy requirements in N transformations which must be mediated by the presence of ATP. Cole and Heil (1981) hypothesized that N reaction rates will eventually equilibrate with P availability, that is, P will become limiting for such N processes to proceed.

Several N processes are known to be affected by P levels in the soil. Janos (1980a,b) and others have indicated that the increase in nodulation and biological nitrogen fixation in those legumes associated with mycorrhizae may be related to the ability of symbiotic fungi to supply the plant with adequate amounts of P (see Cole and Heil, 1981). Munevar and Wollum (1977) found that additions of P increased the amount of N mineralized, and concluded that available P was the rate-limiting factor of organic N release from organic matter. Purchase (1974) determined that low P levels affect nitrification

rates, and concluded that nitrite oxidizers were more sensitive to P availability than ammonium oxidizers.

Although experimental field results are scarce and hard to interpret, there is convincing evidence that suggests strong P-N interactions. Studies including both N and P availability levels will be necessary to more fully understand N cycling processes of ecosystems, adding another dimension to the already complex analyses.

Variability in Field Sampling of Soil N Reactions

Spatial and temporal sampling variability can seriously affect the accuracy and precision of field measurements, which may lead to erroneous interpretation of results obtained. Nevertheless, little attention is generally given to these sampling problems mainly because it would inevitably require longer and more expensive experimentation.

As summarized by Chapman (1964), assessment of the degree of spatial and temporal variability of a process to be investigated, will depend on the number and size of samples taken, number and type of compartments measured, environmental conditions of the site at the time of sample collection, sampling method, and techniques used in the chemical and physical analyses of the samples. In addition, history of the site may be required to determine possible sources of variability.

Spatial variability can occur at micro- and macro-scale levels. Studies which have very small sizes, such as in microbiological investigations, generally contain high variation. For example, inside aggregates in clayey soils denitrification may be occurring, but outside the aggregates there may be sufficient aeration to inhibit this process (Greenland, 1978). On the other hand, the larger the

unit sample size the higher the expected variability as the probability of including heterogeneities increases. In both cases, prohibitively large numbers of samples may be necessary to satisfy all statistical and experimental objectives.

Temporal variability must also be considered. Many processes in nature occur in bursts or pulses. Several physical, chemical and biological parameters must interact together to produce a determined effect that will trigger a specific process. For example, Morris (1981) performed his experiments in a dry year and concluded that, in these conditions, nutrient losses were low. But such results may not be applicable in a wetter year.

Another example of the possible problems associated with figuring both spatial and temporal variability, was discussed by Woodmansee et al. (1981) for N cycling investigations in grasslands. They pointed out that many research studies have assumed that the site is homogeneous, without testing homogeneity, but the analyses performed on small areas were extrapolated to the whole site. Another common mistake was to assume that processes did not vary with time, while the data collected were used to calculate annual budgets and fluxes. In one of the studies by Woodmansee et al., for example, they observed that during one specific year a nitrogen fixation rate of 54 kg N/ha was estimated, but in the two subsequent years, only a rate of 3 kg/ha-yr or less was fixed, a difference of at least 18 times from one year to the next.

It also is important to distinguish between natural variation produced by environmental conditions, and those produced artificially as a result of the method used. This point may be exemplified by

using Hansen and Harris's (1975) work, where a substantial bias and variability in nitrate concentrations were found in samples collected from porous cup samplers. Variability was caused by different intake rates of the cups, by differential plugging of the pores of the samplers over time, and by the various positions in which the samplers were placed.

Recently, a number of workers have discussed the variability problem in sampling soils and vegetation. Bigger (1976) reviewed the causes and patterns of spatial variability in soil N processes, and Warrick and Nielsen (1980) dealt with the variation in other physical soil factors. Chapman (1964), Lee et al. (1979), Colley et al (1981), and others, have studied the variability and distribution patterns associated with nutrients in vegetation. It is important to mention that these and other authors have found that their data did not follow the requisites of normal parametric statistics.

In conclusion, many factors must be considered in order to properly interpret experimental and observational data, although as mentioned before, technical or economical support and availability of time may not be adequate.

Methodological Considerations

In the following sections, a brief review of the several methods used for measuring some of the N processes to be used in this investigation will be presented. The purpose of this section is to provide some justification for the selection of some of the methods used in this investigation.

N Mineralization-Immobilization and Nitrification Techniques

Several procedures have been proposed to measure the actual or potential ability of microbes to transform and release N that may be later utilized by plants. Recent reviews on the subject include those by Dahnke and Vasey (1973), Keeney (1980), and Broadbent (1981). These procedures have been divided into two broad groups: chemical and biological.

In the chemical methods, soils are extracted with different compounds and analyzed for N in the extracts. These methods are considered to be more precise and rapid than the biological methods (Broadbent, 1981), and according to Keeney and Bremner (1966), they are less effected by soil pre-treatments. The major criticisms are related to their inability to simulate microbial activity, and, as a consequence, rates of N transformations and release over time under field or laboratory conditions cannot be estimated (Broadbent, 1981).

Biological procedures include both anaerobic and aerobic incubations. In these cases, soil samples are incubated in the field or laboratory for a period of time and changes in N concentrations (both ammonium and nitrite-nitrate) are determined. Stanford and Smith (1972) proposed a laboratory method to estimate the N mineralization potential and mineralization rate constant for a specific soils type. Basically, the method consists of incubating a pre-leached soil sample under constant moisture for 30 weeks at 35° C, and extracting it several times during the incubation period with calcium chloride and a N-minus solution. A maximum cumulative N concentration level is reached which apparently correlates with actual mineralization rates. According to this and later studies (e.g.,

Stanford et al., 1974), a first-order kinetics model can be used to evaluate these mineralization potentials, although recent investigations by Smith et al. (1980) suggested that such model may give errors and that other models should be used.

Some of these tests have also been strongly criticized because they involve severe manipulations of the soil, such as sieving and pre-leaching treatments, and because they do not take into consideration plant uptake of N and do not simulate field variability (Keeney, 1980; Broadbent, 1981). In addition, soils aerobically incubated, more than those anaerobically incubated, are significantly affected by air drying prior to incubation, by moisture variations during the incubation period, and by the nutrient status of the soil (Keeney and Bremner, 1966).

One of the most often used methods to directly evaluate mineralization rates under field conditions was proposed by Eno (1960). In this case, a soil core is extracted, covered with polyethylene plastic to reduce water losses, and left in the field for a period of time, usually 30 days. But, according to Bremner and Douglas (1971), most commonly used plastic films are unable to rapidly diffuse CO_2 or O_2, and permeability to such gasses varies depending on temperature and moisture content of the sample, effecting the rates of the microbially mediated N processes.

Some advantages of the biological incubation methods include their ability to better simulate microbiological conditions (Broadbent, 1981), and the fact that both ammonification and, in the case of the aerobic incubated soil samples, nitrification processes may be measured simultaneously (Vitousek et al., 1982). Powers (1980)

and others induced that the anaerobic incubation results correlated well with tree growth (see also Keeney, 1980).

Non-Symbiotic Nitrogen Fixation

Several techniques have been used to measure N_2 fixation activity. These have been extensively reviewed by Burris (1974), Hardy and Holsten (1977), Bergersen (1980), and Havelka et al. (1982). Procedures can be grouped as direct or indirect methods.

The direct methods measure N fixation without requiring conversion factors. One approach used is to determine total N changes with time in the soil or in the nitrogen fixing plant. But, because of its low sensitivity, large intervals of time and systems with high fixation activities are needed. In addition, if an open system is used, other field measurements must be made to include other possible inputs and outputs. Another approach is to use $^{15}N_2$ isotope. This technique is about 100 times more sensitive than measuring total N changes with, for example, the Kjeldahl procedure, but is very expensive, requires sophisticated instrumentation, and is time consuming. Also, complications apparently increase when studies are performed in the field, causing problems in interpretation.

Several indirect methods are available. The acetylene reduction method is one of the most popular ones. Among its most notable advantages are the following:

1) It is relatively inexpensive and equipment is readily available;
2) It is very sensitive,
3) Relatively undisturbed samples may be studied;
4) The method can be adapted to field studies without major complications;

5) Because of its sensitivity, the method can be used in systems with low fixation rates

But, the acetylene reduction method also has limitations. These have been discussed by Witty (1979), Knowles (1980), Turner en Gibson (1980), and Berkum and Bohlool (1981) Among them are the following

1) Because method is very sensitive, very careful handling of samples is required. Changes in microbiological activity produced by small variations in temperature, moisture, pressure, or aeration during sample handling may be induced and, as a result, variability of data may increase. Short incubations are recommended for this reason.
2) Besides nitrogen fixation, other microbial processes such as ethylene oxidation are effected by the acetylene gas.
3) Controls used to determine ethylene production in samples with no acetylene, are not adequate. Ethylene normally is metabolized very rapidly by microorganisms, but in the samples containing acetylene gas, such oxidation is inhibited. As a consequence, N fixation rates are overestimated. This problem is usually of greater significance in soil systems having low fixation rates.
4) A conversion factor is required to transform ethylene produced to actual nitrogen fixed. This factor varies depending on the sample used
5) Diffusion of acetylene and ethylene between sampling ports and fixation sites, may cause apparent lags and non-linear results.

Despite from these disadvantages, the acetylene reduction technique is still widely used due to its simplicity, sensitivity and relative cheapness.

METHODOLOGY

Characteristics of the Study Area

The study area of the present investigation is located in Bradford Co., FL (Lat. 29° 52' N, Long. 82° 05' W), on property owned by Container Corporation of America and managed for commercial production of pulp fiber by slash pine (Fig. 2).

History and characteristics of the stands used here were described by Gholz and Fisher (1982). In general, terrain at all plots is flat and soils are poorly drained ultic haplaquods with a subsurface organic horizon (B_h) within 50 cm of the surface, and kaolinitic clay layer (B_t) around 100 cm. These sandy soils have a low ion exchange capacity (2-3 meq/100 g) with the majority of the exchange sites associated with organic matter (Yuan et al., 1967, Pritchett and Comerford, 1983). They are highly weathered, acidic, and very infertile with low organic matter contents (Gholz and Fisher, 1982, Gholz and Fisher, in press). Organic matter and nutrient dynamics in an age sequence of plantation stands, including the 9- and 29-year-old plots used here, have been described by Gholz and Fisher (1982), Gholz, Perry, Cropper, and Hendry (in press), and Gholz, Fisher, and Pritchett (in press).

The climate of the region is warm and humid with a mean annual air temperature of 24.0° C and a minimum of 8.3° C (January), a mean annual precipitation of 1320 mm, and a mean soil temperature of 18.6° C. Some specific conditions encountered during the experimentation

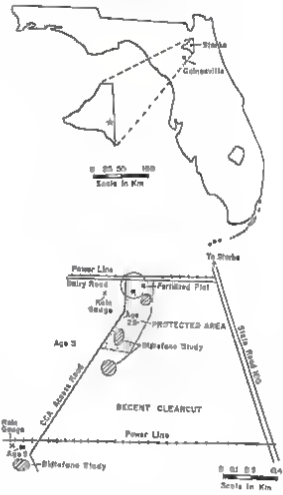


Figure 2 Map of Florida and an inset showing the location the plots used in the present investigation

phases, including water table levels, are presented in Fig. 3 and Table 4.

Characteristics of Study Plots

Three 110 x 55 m plots were selected in a recent clearcut site, and in a 8- and 28-year-old plantation. Within each plot, 15-6 m diameter circular subplots, each separate by 20 m, were established. Prior to the recent harvest, all plots had not been fertilized, thinned, or burned for at least 8 years (Gholz and Fisher, 1982). All sites present comparable soil conditions, and site preparation in all consisted of roller chopping with a weighted drum, burning, and machine bedding and planting.

In general, the vegetation of these plots may be stressed in several ways. Among the most important factors are the very low availability of nutrients in the soil, especially P (Pritchett and Comerford, 1983; Gholz and Fisher, in press; Gholz, Fisher, and Pritchett, in press), and the extreme changes in water regime, especially near the surface where greatest abundance of fine roots develop (White and Pritchett, 1970). Due to the proximity of the water table to the surface, sites flood easily (Fig. 3) during rainstorms, but moisture content drops very fast in the dry period.

Clearcut Area (0 Age)

The clearcut site (0 age), which was harvested in March 1983, had been part of the same plantation block that contained the 28-year-old study plot. Trees were cut at the litter surface, branches removed and left in the area, and stems harvested. No further operations were made. Minimal disturbance of the mineral soil occurred, although, because of some displacement in the litter layer, several portions

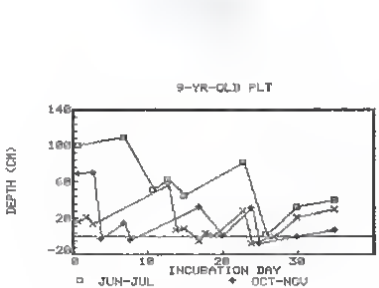


Figure 3. Water table levels recorded during the three experimental phases in the 9- and 29-yr-old plantations

Table 4. Average soil temperature (°C) at 5 cm, and cumulative rainfall (RF, mm) during the three investigation phases in June-July 1983, October-November 1983, and February-March 1984.

		PLANTATION AGE (yrs)					
		Clearcut		5-yr-old		29-yr-old	
		TEMP	RF	TEMP	RF	TEMP	RF
JUN-JUL	x	29.4*	--	26.1	259	25.9	266
	SD	4.9		1.0		0.5	
OCT-DEC	x	--	--	16.6	295	17.9	304
	SD	--		2.5		2.7	
FEB-MAR	x	16.8	--	18.0	314	17.7	318
	SD	1.7		1.3		1.2	

(*) Measured in June-July 1984.

were exposed to direct sunlight and rain drops. In addition to the heterogeneity of the litter layer, small piles of branches and small stems occurred in several places.

No aboveground live vegetation was present in the area for several months following the harvest operations, but after one year some grasses such as Andropogon sp. and Panicum sp., and saw palmette (Serenoa repens (Bi.) Small) plants became established in the area

Nine-Year-Old Plantation

This plantation was characterized by having a relatively open canopy due to its young age and relatively wide spacing. This openness permitted a strong dominance of grasses in the understory, such as those found in the disturbed site, mixed with saw palmetto, gallberry (Ilex glabra (L.) Gray), and Vaccinium sp.

This site was prepared in 1974. Beds are still clearly evident, covering some 70% of the surface, with the balance in interbed troughs. There was no or only a very thing litter layer present, with no humus.

Although all sites flooded at some time, this stand tended to be more prone to this condition (Fig. 3), drainage was slower than in the other areas

Twenty-Nine-Year-Old Plantation

This plantation was a well-stocked stand with relatively sparce understory, mainly composed of saw palmetto, and had a thick, well developed forest floor No signs of beds or interbeds were detected, although some old fire scars were observed. A nearby stand with these same characteristics, was the one harvested and used as the clearcut site.

Treatment Application

Two treatments were randomly applied to 5 of the 15 subplots within each of the plots. PK fertilization and prescribed burning. The remaining subplots were maintained as controls. Calcium superphosphate and potassium chloride were applied with a hand-held spreader, twice (in March and October 1983) at a rate of 50 kg P/ha and 50 kg K/ha.

Burning was done in March 1983, the same week the fertilizer was applied, on 10 x 10 m squares enclosing each of the subplots. Each square was isolated by about 2 m wide strip, raked and/or mowed to expose bare the mineral soil to keep the fire from spreading. At the clearcut plot, fire fronts were started along all inside edges of the squares and allowed to burn inward over the subplot. At the two older sites, a single fire front was established with the fire proceeding against the wind over the subplot (i.e., backfire technique). In general, the burns were relatively hot and uniform except in the clearcut plot where the litter layer was not continuous.

In addition to the above treatments, and as part of an on-going project directed by Dr. H. Gholz (School of Forest Resources and Conservation, University of Florida), a 25 x 25 m plot was established in the 25-year-old study area, about 200 m away from the other treatments. This plot was fertilized with urea, calcium superphosphate and potassium chloride annually for three years (August 1981, 1982, and 1983) at rate of 150 N, 50 P, and 50 K kg/ha. Although itself unreplicated, the plot was large enough to contain 5 subplots as described above.

Processes in the N Cycle Studied

Several microbiologically mediated N processes were studied in each subplot, including the following: net ammonification-immobilization, nitrification, and potential non-symbiotic biological N_2 fixation. In addition, variations in P concentrations and water soluble organic carbon (SOC) were investigated simultaneously with the above studies to determine if there was some relationship with the N processes.

Results from this investigation will be interpreted in the context of results at the stand-level already conducted in the sites, and in this way, the subplot experiments will be integrated with other larger scale experiments.

Details of the procedures used in the study are described in the following sections. Field and laboratory experiments were conducted during three periods in 1983-1984: June-July 1983, October-November 1983, and February-March, 1984.

Measurement of Nitrogen Mineralization and Nitrification

Soil Core Extraction

Three undisturbed cores per subplot were extracted from the A horizon with a 7.6 cm diam. x 8 cm long sharpened PVC tube. Two of the sets of cores were immediately placed in moisture proof bags and returned to the laboratory. The remaining set was left in the field.

The cores brought to the laboratory were incubated for 30 days at 25° C. Cores were divided into two groups: to one of the groups (designed as "saturated"), deionized water was added from below until the water level was about 2 cm above the soil surface. The second group ("unsaturated") was maintained at its initial moisture content

during the incubation by periodically adding deionized water to keep same total core weight. The cores were open to air circulation, but to avoid very fast drops in moisture a thin plastic layer with small holes was placed on top. These two extremes of moisture content were selected to simulate possible N mineralization rates under these moisture conditions which frequently occur in the field, and to have some indication of possible nitrification rates under constant temperature and moisture (in the case of the unsaturated cores) Procedures used above were similar to those described in Keeney (1982).

The third set of cores was incubated in the field for 30 days. A novel incubation procedure was used (Fig. 4) Instead of enclosing the core in polyethylene bag, as suggested by Eno (1960), two nylon mesh bags (with a rigid ring inside that fit tightly against the inner wall of the core), each containing about 10 g (dry weight) of a mixed-bed ion exchange resin (IER, Table 5), were inserted at the top and bottom of the core to isolate the soil. The edges of the core against the ring were sealed with silicon glue to avoid boundary flow of soil solution. In addition, a protective wire mesh screen was placed over both ends. The core was then reintroduced into the hole, making sure there was no space left between the bottom end of the core and the soil, and the top covered with litter.

The top resin bag was designed to trap incoming ions during the incubation period, the bottom resin bag was used to trap ions leaving the soil core. In this way, a mass balance for N could be constructed to determine total mineralization and nitrification (N extracted from

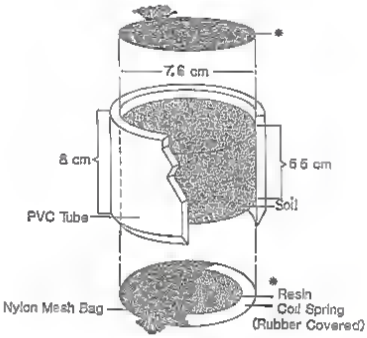


Figure 4 Diagram showing the field incubated soil core. Both ends of the core were isolated with the ion exchange resin bags

Table 5. Chemical and physical characteristics of the mixed bed ion exchange resin (Rexyn 1-300, certified grade, Fisher Scientific, Co.) used in the N mineralization studies.

MESH SIZE (wet, U.S. standard sieve)	16-50
TOTAL EXCHANGE CAPACITY (dry basis)	1.88 meq/g
MOISTURE CONTENT	54.5%
ACTIVE ANION GROUP	RSO_3^-
ACTIVE CATION GROUP	R_4N^+
IONIC FORM	H^+; OH^-
ACTIVE pH RANGE	2-14

the soil + N extracted from the bottom resin bag). Other details are explained in Appendix 1.

Some potential advantages over the plastic bag technique (Eno, 1960) for which I used the resin procedure, include the following:

1) Diffusion of gasses should not be inhibited.
2) Moisture contents of the core can change during the incubation period.
3) Movement of ions by mass flow inside the soil core is possible, avoiding artificial accumulation of inorganic N in the soil solution. In a way, ions trapped by the low IER mimic absorption of nutrients by roots.
4) Once ammonium and nitrate are trapped by the IER, apparently no further transformations occur (Schnabel, 1983, Binkley, in press). This reduces the possibility of N losses through denitrification, and assures that ammonium- and nitrate-N are accurately assessed.
5) An estimation of potential nutrient leaching may be obtained through analyses of the lower resin bags, assuming no uptake by vegetation (as in the recent clearcut site).

In addition, a recent study indicates that little ammonium- or nitrate-N reaches the resin by diffusion from the surrounding soil (Binkley, in press), so that all the N on the resins should be a result of water flow vertically down through the cores.

To represent initial conditions of the soil cores (before incubation, (three replicate soils samples/subplot were collected at the same depth and without including the litter layer around the mineralization core area. Each of the three replicates were

eggregeted, mixed end enelyzed for ammonium, nitrete, inorgenic P, pH, totel nitrogen (TN), end other cations (Appendix 2).

Chemical Analysis Procedures

Anelyses of soil samples were performed es follows

For the determination of inorgenic N, fresh soil wes mixed end screened with e 2 mm opening steinless steel sieve. In the cese of the seturated cores, soil was first dreined for 20 to 30 min before mixing (drained water was collected and analyzed for N, see Appendix 1). A portion of the fresh soil equivelent to 10 g of dry soil was mixed with 2 N KCl for 1 hr, filtered with Whatman # 42 filter paper and stored in the refrigerator at 5° C until it was enalyzed (Keeney and Nelson, 1982). Ammonium- end nitrite-nitrate-N concentretions were detected using the automatic colorimatric procedures of e Technicon Autoenelyzer II (Technicon Industriel Systems, 1978).

Another portion of the sieved fresh soil equivelent to 10 g dry weight, was mixed with 100 ml of deionized water for 1 hr in e glass flesk and then filtered with a 0.02 micrepore filter. The filtrate was manipuleted end digested immedietely efter, following the procedure by Menzel end Vecare (1964), end stored for e later determination of water soluable organic carbon (SOC). Each sample conteined 1 ml of filtrate, 0.2 ml of 10% phosphoric acid, end 1 ml of e saturated solution of potessium persulphate. Samples were purged of inorganic C by bubbling with oxygen gas, and then seeled. Once seeled, samples were digested in autocleve for 30 min at 130° C and anelyzed for CO_2 using en infrared (IR) detector

Gravimetric moisture contents of the fresh soil were determined by weighing 10 g of the sieved soil, oven-drying it at 100° C for 24 hrs, and reweighing.

Remaining soil was air dried for 2-3 weeks, sieved, and sent for pH, organic matter, cation and inorganic P analyses to the Analytical Research Laboratory, University of Florida. This laboratory uses the following procedure to determine extractable Al, Ca, Fe, K, Mg, Mn, P and Zn. 5.0 g of mineral soil is extracted for 5 min with 20 ml of Melich I extracting solution (0.05 N HCl in 0.025 N H_2SO_4, Melich, 1953). The filtrate is analyzed by atomic absorption spectrophotometry, using a Perker-Elmer 5000 spectrophotometer, except for P. P is determined colorimetrically using the Technicon Autoanalyzer II (Technicon Industrial Systems, 1976). Soil pH is determined in a 1:2 soil:water suspension, and organic matter is determined using the Walkley-Black heat of dilution method (Donohue, 1982). In addition, total nitrogen was analyzed using the micro-kjeldahl procedure (Bremner, 1965).

Inorganic N and P absorbed in the IER were extracted by mixing 2 g of air dried resin in 50 ml 2 N KCl solution for 1 hr, and filtering it with Whatman # 42 filter paper. The filtrate was analyzed for ammonium, nitrate (plus nitrite), and inorganic P using the Technicon Autoanalyser II.

It was found that, during the analysis for ammonium extracted from the resin, some kind of contamination inhibited the color development in the Technicon Autoanalyzer or lead to overestimates when the steam distillation was used. After several laboratory tests, it was found that

1) By increasing the concentration of sodium hypochloride from 6 to 9 ml/100 ml, and decreasing the concentration of sodium nitroprusside from 0.30 to 0.25 g/1000 ml in the Technicon procedure, and by diluting the sample, low levels of ammonium could be readily detected.
2) When the above changes were made and the sample diluted 2.5 times, a linear relationship between ammonium detected and added to the IER was obtained in the range of 0 to 6 mg N/l.
3) When a separate cation-only resin was purchased, and the experiment repeated, no interference occurred during the steam distillation, and only a slight positive overestimation occurred in the Technicon. This results may indicate that the anion portion is causing the problems observed in the analysis of the mixed resin bed. A similar conclusion was reached by Hart and Binkley (1984).

In the present study, solution extracted from the resin was analyzed using the modifications mentioned. A standard curve relating the amount of ammonium extracted from the resin and detected in the Technicon, after the solution was diluted 2.5 times, to that actually added to the resin, was developed in the laboratory and used to estimate the amount of ammonium trapped in the field resin (Appendix 6).

Measurement of Non-Symbiotic Biological N_2 Fixation

Undisturbed soil cores (10.8 cm diameter x 16.5 cm long), not including the litter layer, were extracted from each subplot near the field mineralization cores between 9 and 11 A.M. on each of the sampling dates.

Each of the cores was sealed with a septum and a rubber "Jim" cap at the top and bottom ends, respectively, transported to the laboratory, and then prepared for the acetylene gas injection. Sixty ml of air were then extracted from each core, and replaced with the same amount of acetylene gas, this gave a final acetylene concentration of approximately 10% (v/v). Cores were then incubated for 8 hrs at temperatures similar to those encountered in the field during the collection period (i.e., 27° C, 18° C and 23° C for the summer, fall, and spring phases, respectively). After incubation, 0.05 ml of the soil core atmosphere was extracted with a syringe and injected into a Variam Gas Chromatograph (model 3700) for acetylene and ethylene detection. The gas chromatograph characteristics were as follows:

Oven temperature: 90° C

Injection port temperature: 140° C

H_2 flame ionization detector temperature: 170° C

Carrier gas: N_2

Column pressure: 1.41 kg/cm^2

Column type: Porapak N; mesh size: 80/100

Column size: 180 cm long x 0.3 mm diam.

Acetylene gas was used as an internal standard. The concentrations of the acetylene and ethylene standard gasses were estimated with the standard gas law assuming 25° C temperature and 1 atmosphere of pressure.

The formula described by Hardy and Halsten (1977) was used to calculated moles of ethylene/core-hr produced and N_2 fixed/day. A 5:1 ethylene:N_2 ratio, and a 18 hrs/day activity was assumed to

estimate the nitrogen fixed. Since the validity of these assumptions was not verified, and, because this experiment used short term incubations, values only represent potential N_2 fixed in the field (see Smith et al., 1982).

After the incubation, each core soil sample was mixed, sieved and air dried. Analyses for cations, pH, organic matter, and total nitrogen were accomplished as above (Appendix 3). Gravimetric moisture contants were also determined.

Statistical Analysis

The N and P mineralization data were analyzed using the General Linear Models (GLM) procedure of the Statistical Analysis System (SAS). A split-split plot in time model was utilized to determine significant main effects or interactions between plantation age, treatment, incubation method, and season (Freund and Littell, 1981; R. Lynch, pers. comm., 1984). Plantation age effects, treatment effects, and their interactions were tested with the "replication (plantation age*treatment)" factor as the error term. A similar design was used for the non-symbiotic N_2 fixation, except that incubation method was not included in the model and arithmetic values were transformed to base 10 logarithms before the statistical analysis. The transformation was performed to stabilize the variances so that standard parametric statistical analyses could be utilized (Gomez and Gomez, 1984). Final presentation of the means was obtained by retransforming the logarithm values

A least-square means procedure was used to determine significant differences between means. Only pre-planned comparisons were used to ensure the validity of tests and attained probability levels

Comparisons among plantation ages, treatments, incubations methods, and seasons were made. In addition, a stepwise linear regression analysis was performed to determine if selected surface soil chemical parameters affected the N processes.

RESULTS

Ammonification

Seasonal Effects

Summer During the summer a highly significant plantation age-incubation method interaction was found for all treatments ($p = 0.008$). Initially the 9-year-old plantation had a 30% lower ammonium-N concentration than the clearcut ($p = 0.08$) and the 29-year-old ($p = 0.05$) plantation (Fig. 5). But, after the one month field and laboratory incubation period, all areas tended to have similar levels of ammonium-N, although they were somewhat lower in the 29-year-old plantation (significantly different from the other sites only for the saturated laboratory cores).

The clearcut and 9-year-old plots had significantly higher net ammonification rates than the older plantation for all the incubation methods (Fig. 5). In the older plantation, N tended to be immobilized.

When incubation methods were compared, the field and saturated laboratory cores from the clearcut and 9-year-old plantation had higher rates of net ammonification (at least 4 mg N/kg-mo compared with less than 2) than the unsaturated cores. Rates of ammonification in the unsaturated laboratory cores were low and were significantly different from the field and saturated laboratory cores in the clearcut plot, and the saturated cores in the 9-year-old plantation.

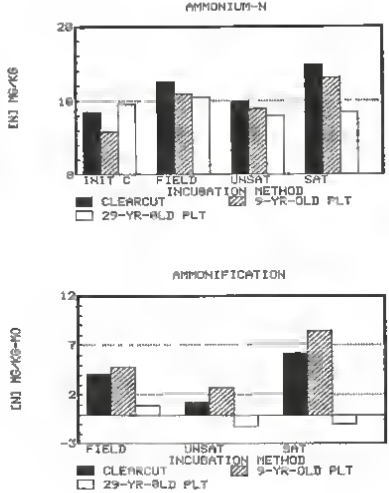


Figure 5. Summer soil ammonium-N concentrations and ammonification rates for the various plantation ages and incubation methods

No significant differences among methods were observed for the 29-year-old plot

In addition, a significant ($p = 0.08$) interaction between plantation age and treatment for all incubation methods was observed. In the clearcut site, ammonium-N concentrations of control plots were not significantly different ($p = 0.05$) from the burned or PK fertilized plots (Fig. 6). In the 9-year-old plantation, control plots were significantly higher ($p = 0.05$) than burned plots, and in the 29-year-old plantation no differences among the treatments were observed. In general, net ammonification rates tended to be lowest in the burned plots, with relatively high net immobilization rates in the oldest plantation (Fig. 6).

Fall. In the fall, only a significant treatment-incubation method interaction ($p = 0.09$) was found (Fig. 7) No effect of plantation age was detected. In this season, the laboratory incubation cores from the burned and PK sites showed higher concentrations of ammonium-N than controls (Fig. 7), although only the cores from the fertilized plots were significantly different ($p = 0.05$). There was also an apparent stimulation of ammonification rates by the burned and PK treatment in the laboratory cores (Fig 7). A maximum average rate of 10.1 mg of N/kg-mo was obtained for the saturated laboratory cores from the PK treatment. On the other hand, some immobilization of ammonium-N was observed in the field cores, contrary to what was found in the summer.

When incubation methods were compared within treatments, in all cases the laboratory cores had at least double the amount of ammonium-N over the initial conditions ($p = 0.05$, Fig 7), and had the

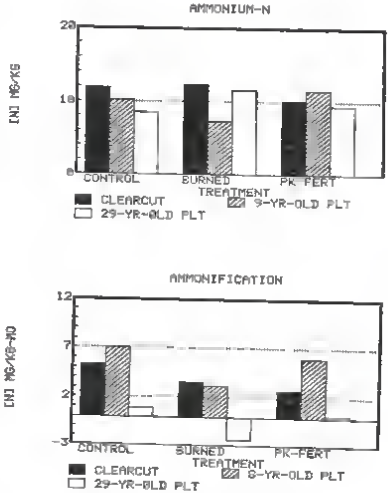


Figure 6. Summer soil ammonium-N concentrations and ammonification rates for the various plantation ages and treatments.

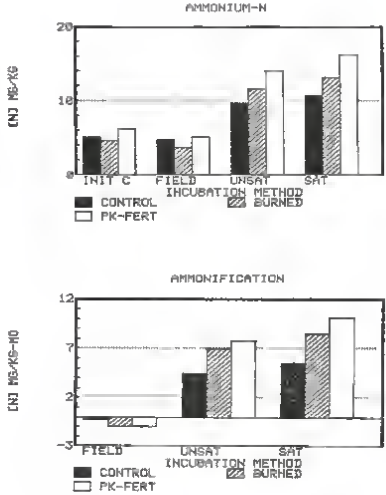


Figure 7 Fall soil ammonium-N concentrations and ammonification rates for the various incubation methods and treatments

highest net ammonification rates (Fig. 7). The field and initial conditions cores were statisticaiiy similar, so that no net ammonification occurred

Spring. In the spring, a significant plantation age-incubation method interaction was again observed ($p = 0.002$), while treatment effects were not statistically significant. As in the fall initial condition and field core values were very similar when incubation methods were compared (Fig. 8). Aiso, no differences were detected when ammonium-N concentrations in these core sets were compared among the plantation ages. Net ammonification rates were relativeiy low in the field cores for ail the plantations (Fig. 8).

On the other hand, in the laboratory incubated cores, some significant differences were found. This time, average ammonium-N concentrations in the unsaturated laboratory cores from the 29-year-old plantation, were approximately double the concentretians of the 9-year-old or clearcut areas ($p = 0.05$). When the saturated laboratory cores were analyzed, the 9-year-old plantation had around 30% higher cancentrations than the clearcut or 29-year-old sites, although differences were not statisticeiiy significant (Fig. 8).

In generai, the laboratory incubated cores had ammonium-N ieveis at least 50% greater than the initiai conditions (significant at $p = 0.05$). The oniy exception was the unsaturated cores in the clearcut site (Fig. 8).

Unsaturated and seturated cores tended to have higher ammonification rates (of at least 4 mg/kg-mo), except for the unsatureted cores in the clearcut area. Field incubated cores had significantly ($p = 0.05$) lower (Fig. 8) finel concentrations than the

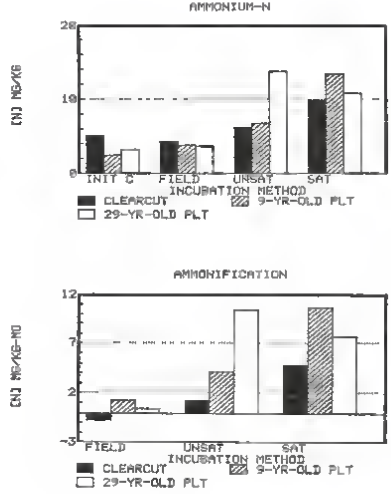


Figure 8. Spring soil ammonium-N concentrations and ammonification rates for the various plantation ages and incubation methods.

laboratory incubated cores for all sites and no significant ammonification was observed over the 30-day period.

Plantation Age Effects

Clearcut. A significant interaction ($p = 0.0001$) between season and incubation method was observed for each of the plantation ages. In the clearcut site, lower ammonium-N concentrations were found in the initial condition and field cores during the fall and spring seasons (Fig. 9). This decrease was significant at the 0.05 probability level, and, in some cases, amounts were almost 3 times less than the values in the summer. Fall and spring levels were statistically similar. On the other hand, the laboratory incubated cores had a significant ($p = 0.05$) reduction in their ammonium-N concentrations in the spring only. Summer values were at least double of those found in the other seasons (Fig. 9).

When seasonal net ammonification rates were compared (Fig. 9), a relatively strong drop in activity was observed in the field cores during the fall and spring seasons: from more than 4 mg N/kg-mo in the summer, to less than 0 mg in the other seasons. Saturated laboratory cores showed no significant differences in net ammonification rates with season, but the unsaturated cores had significantly ($p = 0.05$) higher rate in the fall when compared with the summer or spring values (Fig. 9).

Nine-year-old plantation. In the 9-year-old plantation, field ammonium-N concentrations also tended to decrease in the fall and spring (Fig. 10). Many similarities were observed when this plantation age was compared with the clearcut area. In the 9-year-old site, initial concentrations were half the concentrations of the

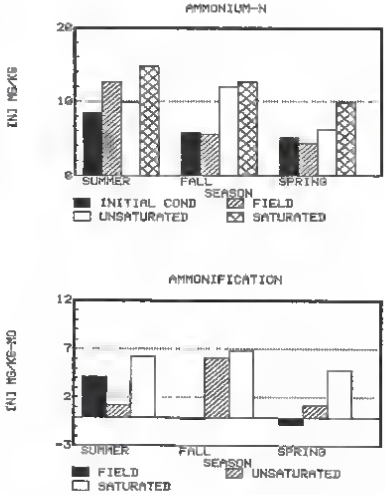


Figure 9 Soil ammonium-N concentrations and ammonification rates in the clearcut site for the various seasons and incubation methods.

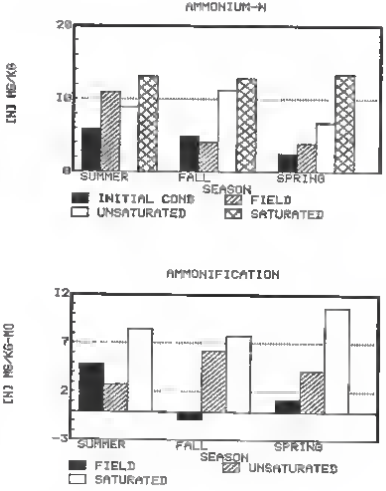


Figure 10 Soil ammonium-N concentrations and ammonification rates in the 9-yr-old plantation for the various seasons and incubation methods

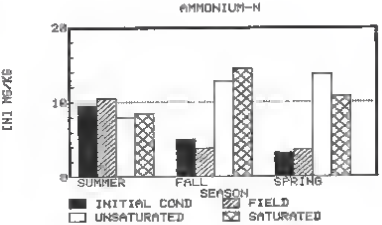
spring ($p = 0.05$) although they were similar to those of the fall. Field incubation cores also had significantly lower ($p = 0.05$) concentrations in both the fall and spring seasons, about 1/3 of those in summer (Fig. 10). The unsaturated cores showed a significant increase in ammonium-N levels during the fall ($p = 0.05$) when compared with summer values, but dropped in the spring to values similar to the summer. Saturated core concentrations tended to increase in the spring, but were not significantly different than in the summer (Fig. 10).

Net ammonification rates showed trends similar to the concentration changes: they were low in the field cores in the fall and spring, and were similar or higher (as much as 10.7 mg of N/kg-mo) in the laboratory cores for the same seasons (Fig. 10).

Twenty-nine-year-old plantation. For the 29-year-old plantation similar trends to the other locations were demonstrated: a significant ($p = 0.05$) decline in ammonium-N concentrations in the fall and spring for the initial conditions when compared with the summer, and a significant ($p = 0.05$) increase in the same periods for the laboratory cores (Fig. 11).

Net ammonification rates reflected patterns of ammonium-N concentrations (Fig. 11), except in the field cores where no differences among seasons were observed. In the laboratory cores, a very strong increase ($p = 0.05$) in rates was observed in the fall and spring when compared with the summer.

When the NPK fertilized site was included in the statistical analysis of the 29-year-old plantation, there was a significant ($p = 0.03$) three-way interaction (treatment-incubation method-season, Figs.



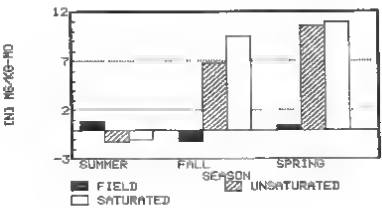


Figure 11 Soil ammonium N concentrations and ammonification rates in the 29-yr-old plantation for the various seasons and incubation methods.

12-13). In ganaral, the following trends were datarminad whan the NPK treatment was compared with tha other treatments, or among the incubation methods within tha various saasons

1) There was a 5-fold increasa from summer to fall (significant at p = 0.05) in the initial ammonium-N concantrations on tha NPK site following tha August 1983 fartilizatron.

2) Thara was a 5-fold dacreasa (p - 0.05) in ammonfum-N concentretions from fall to spring aftar anothar 4 amnths had passed.

3) Net ammonification rates ware high in tha fiald and saturated coras during tha fall, with avaraga ratas ranging from 23.1 to 36.3 mg N/kg-mo (Fig. 13), whila tha unsaturated cores showed a relatively high negativa valua of -8.0 mg N/kg-mo for tha same parfod. In both casas, fall rates ware significantly diffarent (p = 0.05) from summer ratas.

4) Summer ammonification rates were greater than spring ratas from 2-5 mg N/kg-mo in spring comparad to 5-11 mg N/kg-mo fn summer (significantly diffarent at p = 0.05 for the field and unsaturated cores).

5) When the NPK fertilizad sita was compared with tha othar treatments in tha summar (Fig. 12), ammonium-N concentrations were similar in tha initial conditions cores, but they were significantly higher (p = 0.05) after the incubation parfod when compared with the other traatments

6) After the August 1983 NPK fartilization (fall), ammonium-N concentrations ware 5-8 times higher than tha non-N fartilized plots (p = 0.05, Fig. 12).

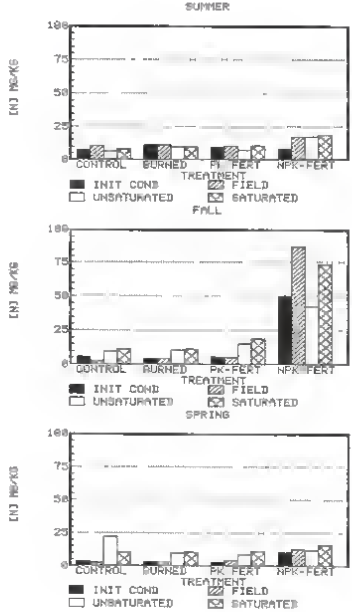


Figure 12. Soil ammonium-N concentrations in the 29-yr-old plantation for the various seasons, treatments, and incubation methods.

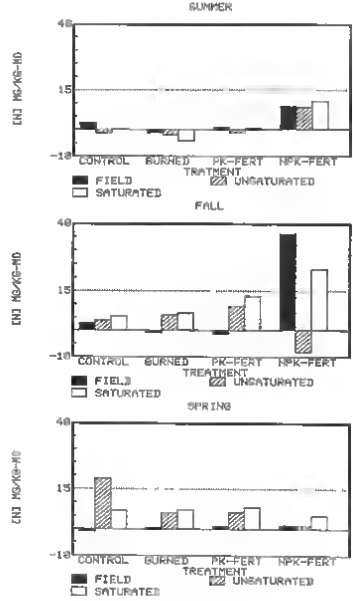


Figure 13 Soil ammonification rates in the 29-yr-old plantation for the various seasons, treatments, and incubation methods

7) Ammonification rates (Fig. 13) were statistically ($p = 0.05$) higher in the NPK site in the summer and fall when compared with rates observed for other treatments.

8) During the spring, ammonification rates dropped and were statistically similar to rates observed in the other treatments except in the unsaturated cores where they were significantly lower than controls (Fig. 13)

Summary

1) At the end of the summer incubation period, ammonium-N concentrations tended to be similar for all treatments and plantation ages, although initial concentrations were different.

2) Relatively high initial ammonium-N concentrations in summer in the 29-year-old plantation apparently led to relatively low ammonification rates.

3) Saturated laboratory cores from the clearcut, 9-, and NPK fertilized 29-year-old plantations collected in the summer tended to have the highest ammonification rates followed by field incubated cores.

4) No statistical differences in ammonium-N concentrations or ammonification rates were observed among treatments in the summer, except in the 9-year-old plantation where burned plots had lower values.

5) No effect of plantation age was observed in the fall

6) No statistical differences were observed in ammonium-N concentrations between initial conditions and field incubations in any treatment or plantation age in the fall or spring.

7) Ammonification rates in the field were significantly lower in the fall and spring when compared with other incubation methods.

8) Field ammonification rates were low in all the seasons in the 29-year-old site when not fertilized with NPK, although ammonium-N concentrations at the end of the incubation periods were similar to those found in the other plantations.

9) Laboratory incubations were significantly effected by all treatments in the fall, although, in the spring, no significant effects were observed.

Nitrification

Seasonal Effects

Summer: A three-way interaction (plantation age-treatment-incubation method) was detected ($p = 0.20$) for the summer nitrate-N concentrations (Fig. 14). No differences in final NO_3-N concentrations were determined in the control or burned plots when plantation ages were compared within each of the incubation methods.

In the PK fertilized plots, field and unsatureted cores in the 9- and 29-year-old plantations tended to have higher final concentrations of nitrate-N than in the clearcut area. Nitrate-N levels in the field cores of the 29-year-old stand were more than 3 and 2 times higher than in the 9-year-old stand and clearcut site, respectively ($p = 0.05$, Fig. 14). For the unsaturated incubation, the 9- and 29-year-old plantations contained about 2 times more nitrate-N concentrations then the clearcut area, but they were not statistically significant at the 0.05 level.

Results were variable when treatments were compared within plantation age and incubation method. In the clearcut treatments did

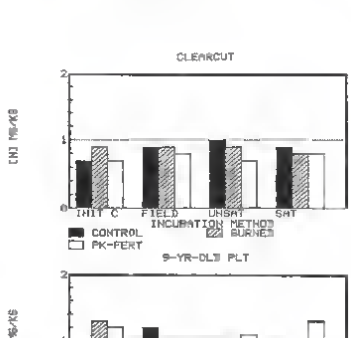


Figure 14 Summer soil nitrate-N concentrations in the various plantation ages, treatments and incubation methods

*Non estimate

not have any effect, but in the 9- and 29-year-old plantations, there were some differences However, no particular trends were observed because, depending on the incubation method, the treatments showed divergent tendencies. For example, field incubated cores from the PK fertilized plots in the 9-year-old plantation had lower concentrations of nitrate-N than the controls, but in the unsaturated and saturated cores, concentrations tended to be similar (Fig. 14). In the 29-year-old plantation, on the other hand, the unsaturated and field cores from the PK plots had higher nitrate-N values when compared with the control.

When the incubation methods were studied within plantation age and treatment (Fig. 14), two main results were obtained. First, no significant differences were observed among treatments in the clearcut site. Second, mixed trends were observed in the 9- and 29-year-old stands depending on the incubation method. In the 29-year-old stand, the field and unsaturated cores collected from the PK plots tended to have higher nitrate-N concentrations than for the other incubation methods

In general, no significant trends were observed when nitrification rates were calculated (Fig. 15), except that all values were very low. It is important to mention that several replications collected in this period were lost due to chemical analysis problems.

Fall. When fall nitrate-N concentrations were studied, only the main effects for incubation method and plantation age were statistically significant ($p = 0.0001$ and 0.14, respectively, Fig. 16). Within incubation method, the unsaturated cores had about 2 times more nitrate-N than in the initial conditions cores ($p = 0.05$),

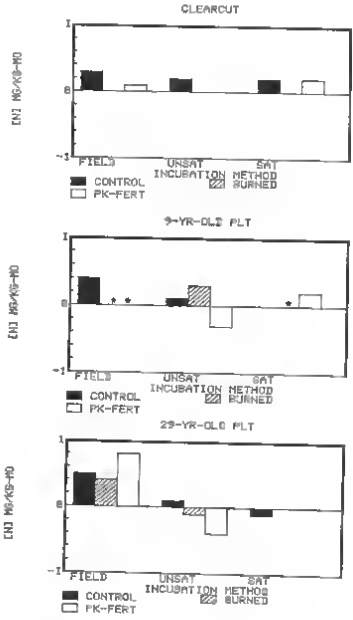
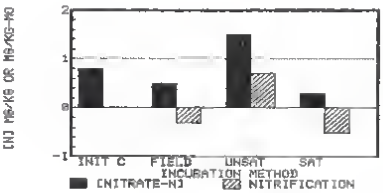


Figure 15 Summer soil nitrification rates in the various plantation ages, treatments and incubation methods

*Non estimate



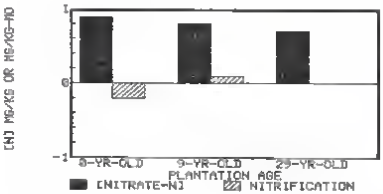


Figure 16. Fall soil nitrate-N concentrations and nitrification rates for the various plantation ages and incubation methods

on the other hand, field and saturated cores had less nitrate-N ($p = 0.05$, Fig. 16). The field and saturated cores produced negative balances when initial condition concentrations were subtracted (Fig. 16).

Within plantation age, the clearcut site had significantly higher ($\alpha = 0.05$) initial levels of nitrate-N than the 29-year-old plantation, but was not different from the 9-year-old plantation (Fig. 16). No significant differences were observed in nitrification rates (Fig. 16).

Spring. During the spring, an interaction between plantation age and incubation method was found ($\alpha = 0.05$, Fig. 17). No significant differences were observed when nitrate-N concentrations for the initial conditions, field, and saturated cores where compared among stand ages, except for the unsaturated cores from the clearcut which had nitrate-N levels over 9 times higher than those for the other two areas ($p = 0.05$, Fig. 17). Nitrification rates were also high in these cores, reading 3.9 mg N/kg-mo (Fig. 17).

When incubation methods were compared within plantation age, only the unsaturated cores collected from the clearcut area showed a statistically significant different from the other methods ($p = 0.05$, Fig. 17); unsaturated values were at least 6 times larger. In addition, a strong increase in nitrification rates was observed (Fig. 17).

Plantation Age Effects

Clearcut. Nitrate-N concentrations were also compared by seasons within each of the stand ages studied. Concentrations from the clearcut area increased significantly in the unsaturated

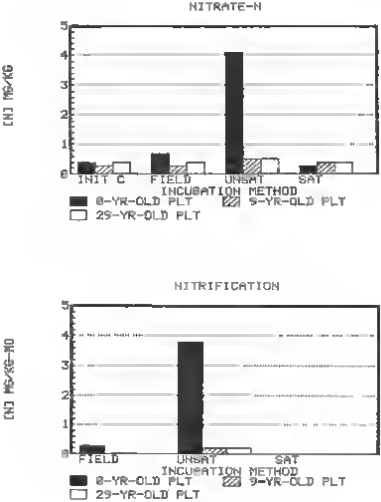


Figure 17 Spring soil nitrate-N concentrations and nitrification rates for the various plantation ages and incubation methods

laboratory cores (Fig. 18). In the fall they were 2 times larger ($p = 0.08$), and in spring they were 4.5 times larger ($p = 0.05$) when compared with summer values. The saturated incubated cores had the lowest concentrations in fall and spring, but were similar to the other cores in the summer.

Nitrification rates in the clearcut site (Fig. 18) behaved similarly to the nitrate-N concentrations: the unsaturated cores tended to have the highest rates in the fall and spring seasons. In addition, relatively high negative values were observed in the fall for the field and saturated cores which may indicate that denitrification occurred.

Nine-year-old plantation. In the 9-year-old plantation, spring nitrate-N concentrations were lower than in summer (Fig. 19), differences were significant ($p = 0.05$) in the initial conditions and unsaturated cores. Nitrification rates (Fig. 19) tended to be higher in the unsaturated cores in the fall. In the other cases, almost no changes were observed, except for the saturated cores where relatively high negative values were detected.

Twenty-nine-year-old plantation. In the oldest plantation, the spring nitrate-N values were also lower than those in the summer (Fig. 20), and were significant ($p = 0.05$) for all incubation methods. Fall values were also lower in the field and saturated incubated cores; the decrease was significant at the 0.05 level and values were around 1/3 of the summer values (Fig. 20). Unsaturated cores, on the other hand, had higher values in the fall ($p = 0.05$), but dropped in the spring ($p = 0.05$) when compared with the summer.

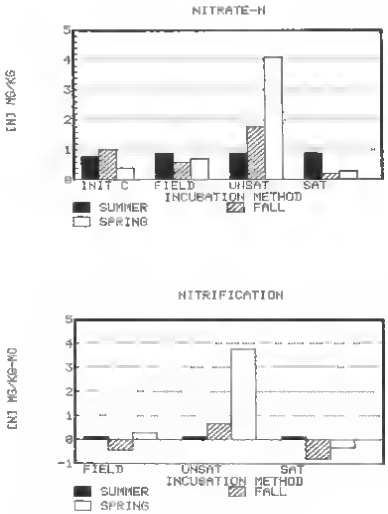


Figure 18. Soil nitrate-N concentrations and nitrification rates in the clearcut site for the various seasons and incubation methods.

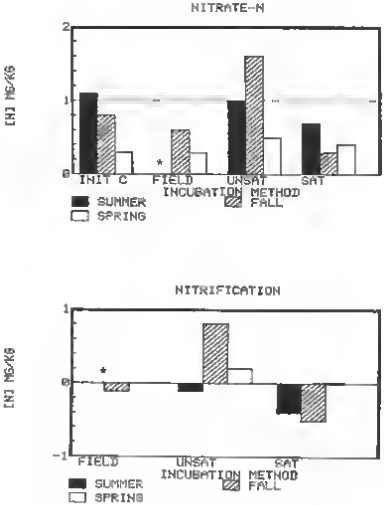


Figure 19. Soil nitrate-N concentrations and nitrification rates in the 9-yr-old plantation for the various seasons and incubation methods

*Non estimate

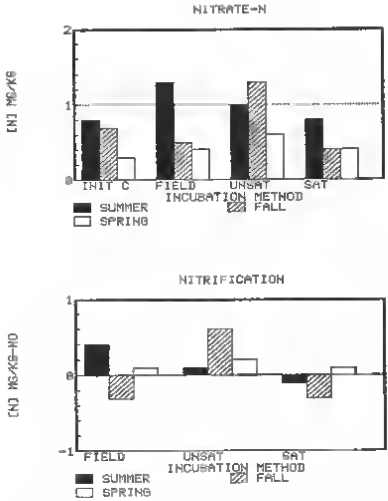


Figure 20. Soil nitrate-N concentrations and nitrification rates in the 29-yr-old plantation for the various seasons and incubation methods

Nitrification rates (Fig. 20) tended to be near 0 or negative for the majority of the cases, except for the field cores in the summer and the unsaturated cores in the fall where values were relatively high (more than 0.4, mg N/kg-mo). No differences were observed in the spring.

When the NPK treatment was added to the statistical analysis of the 28-year-old plantation, a 3-way interaction (treatment-incubation method-season) was significant ($p = 0.0001$, Figs. 21-22). In the summer, no differences were determined among the treatments, but in the fall, after the fertilization, the NPK plots had very high concentrations of nitrate-N relative to the other plots (Fig. 21). This was also reflected in the fall nitrification rates (Fig. 22) where the NPK plots had much higher rates than the controls ($p = 0.05$) for the field and unsaturated cores (15.9 and 9.0 mg nitrate-N/kg-mo, respectively). The saturated cores, on the other hand, had a negative value of -24.2 mg N/kg-mo (Fig. 22). This result was expected as anaerobic conditions promote denitrification of the nitrate-N already present and inhibits further nitrification.

In the spring, the only significant effect was that the unsaturated cores from the NPK treatment had much higher values (Fig. 21).

When the incubation methods were compared within the NPK fertilized treatment, no statistical differences in the nitrate-N levels were found in the summer period, although field cores had double the concentration of the other cores. In the fall, the field and unsaturated incubated cores had higher concentrations of nitrate-N (Fig. 21) with a large portion extracted from the lower ion exchange

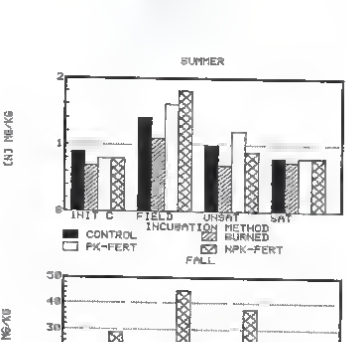


Figure 21. Seasonal soil nitrate-N concentrations in the 29-yr-old plantation for the various treatments and incubation methods. Note change in scale

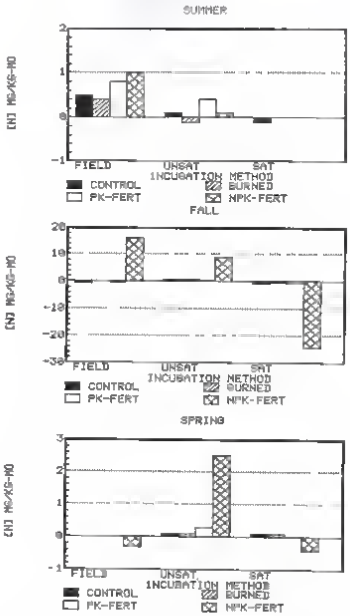


Figure 22. Seasonal soil nitrification rates in the 29-yr-old plantation for the various treatments and incubation methods. Note change in scale

resin, in the case of the field cores (see Appendix 1), (all comparisons were significant at $p = 0.05$ relative to the initial concentrations). The saturated cores had about 6 times less nitrate-N when compared within the initial conditions levels ($p = 0.05$). In spring, nitrate-N levels were back to values similar to those found in summer, except for the unsaturated laboratory incubations where values were still more than 4 times larger ($p = 0.05$) than for the other incubations. Nitrification rates were also significantly ($p = 0.05$) higher in the unsaturated cores (Fig. 22).

Summary

1) No effects of treatment on nitrification were observed, except for the NPK fertilized plots which had greater nitrate-N concentrations and nitrification rates in the fall.
2) There were no effects of plantation age, except for the clearcut (0 age) site which had greater nitrate-N concentrations and nitrification rates in the fall and spring.
3) Unsaturated laboratory cores showed the highest nitrification rates compared with the other incubation methods.
4) A strong decrease in nitrate-N concentrations was observed in the saturated laboratory cores in the NPK fertilized plot after the incubation period, indicating rapid denitrification of nitrate-N.

Potential Non-Symbiotic Biological N_2 Fixation

A significant ($p = 0.007$) three way interaction between plantation age, treatment and season was found when potential non-symbiotic biological nitrogen fixation rates were analyzed (Fig. 23).

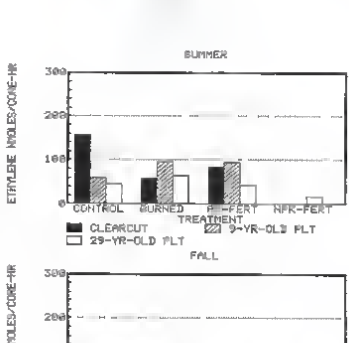


Figure 23— Potential non-symbiotic nitrogen fixation rates (acetylene reduction) in the various plantation ages, treatments and seasons

Plantation Age Effects

When plantation ages were compared within seasons and treatments, the following results were obtained (Fig 23):

1) Control cores from the clearcut area had higher (at least 2 times larger) rates than the controls of the 9-year-old and 29-year-old plantations. These were significantly different ($p = 0.05$) in the summer, but, in the fall, only the 29-year-old and, in the spring, only the 9-year-old plantations were significantly lower from controls.

2) In the burned plots, summer and fall rates in all the plantations were statistically similar. But in the spring, the clearcut rates were about 2 and 3 times higher than those from the 9- and 29-year-old plantations, although they were significantly different ($p = 0.05$) only when compared with the oldest plantation.

3) In the PK plots, no differences between plantation age were obtained for the summer or fall. In the spring, the 29-year-old plantation had rates 2.7 times higher ($p = 0.05$) than the clearcut area.

Treatment Effects (Excluding NPK Site)

When treatments were compared within plantation age and season, no differences were observed in the summer or fall, except in the burned plots from the clearcut where they were significantly lower than controls in the summer, and in the burned plots from the 29-year-old plantation where they were significantly higher than controls in the spring (Fig 23). During the spring, rates from the control and burned plots from the clearcut area were at least 2.7 times higher

than those found in the PK plots, and they were statistically different ($p = 0.05$). In the 9-year-old and 29-year-old plantations, PK plots had higher rates when compared with the other treatments, but were significantly different only in the 29-year-old plantation when compared with the burned plots (Fig. 23).

Seasonal Effects

When seasonal rates were compared within plantation age and treatments (Fig. 23), the following results were obtained:

1) The control plots from the clearcut and 9-year-old sites had statistically similar rates among seasons, although there was a 50% drop in the clearcut during fall. In the 29-year-old stand, on the other hand, spring rates were at least 2.7 times larger than summer and fall rates ($p = 0.05$).
2) In the burned plots from the clearcut area, spring rates were about 4.3 and 5.5 times larger than the summer and fall rates ($p = 0.05$). In the 9-year-old stand, spring rates were also larger ($p = 0.05$) than fall but were statistically similar to summer rates (about 4 and 1.5 times higher, respectively). No changes in seasonal rates were found in the 29-year-old stand.
3) Rates in the PK fertilized plots from the clearcut area showed no seasonal differences. In the 9-year-old plantation, fall values were significantly lower ($p = 0.05$) than summer or spring values, and in the 29-year-old stand, spring rates were 10.4 and 5.3 times larger than fall and summer values, respectively ($p = 0.05$).

NPK Fertilization Effects

A separate statistical analysis was performed in the oldest plantation to determine potential nitrogen fixation trends when the

NPK treated plots were included. A significant ($p = 0.04$) treatment-season interaction was obtained.

In all seasons, the NPK core rates were consistently lower when compared with the other treatments, and they were significantly different when compared with the control core rates in the fall and spring ($p = 0.05$, Fig. 23). No statistical differences were observed when NPK core rates were compared among the seasons, except that spring rates were 2 times higher than the fall rates.

Substrate Effect

Some preliminary studies were performed using litter layer and decomposed wood from the 29-year-old plantation (Table 6). No statistical analysis was made on the data and only three replicates per substrate were collected. Results indicated very high activity in the decomposing wood as opposed to the litter layer, which was 56 times less active. Rates in the wood decreased in the spring (March) when compared with the summer (August) values.

Summary

1) Control plots from the clearcut site tended to have higher potential non-symbiotic fixation rates than the controls of the other plantations.
2) Burning and PK fertilization apparently had a negative effect in the clearcut site, but had not effect or had a stimulatory effect in the other plantations.
3) In the 29-year-old plantation NPK fertilized plots had consistently lower potential fixation rates than the other treatments.
4) Potential N_2 fixation rates were highest in the summer and spring.

Table 6. Seasonal potential non-symbiotic N_2 fixation (nmoles ethylene/core-hr) in the 29-yr-old plantation for the various substrates. Standard deviations in parentheses

	SEASON	
Substrate	Summer	Spring
Litter	--	4.3 (1.7)
Wood	513.4 (289.7)	219.3 (203.5)
Mineral soil (control plots)	87.9 (58.8)	46.0 (30.4)

5) Very high variability in acetylene reduction was observed, especially in the spring.

6) Very high rates of fixation were observed in decaying wood compared with those of the soil. Essentially no activity was detected in the litter.

DISCUSSION

Ammonification

The amount of nitrogen available for vegetation uptake is largely dependent on mineralization rates, especially in unfertilized areas (Cassman and Munns, 1980; Paster et al., 1984). But rates are controlled by a series of complex relationships between biotic factors, such as species composition (various plant species may stimulate or inhibit soil N reactions through production of secondary chemicals) and organic matter quality (nutrient concentrations, lignin concentration, etc.), and abiotic factors, such as temperature, moisture content, nutrient availability, and pH. Because mineralization is a microbially mediated process, small variations in one or more of these factors can lead to very different observed rates.

In the present investigation I found that ammonification rates were variously affected by plantation age, season, treatment, initial ammonium-N concentrations, and incubation technique.

Plantation Age Effects

During the summer (Figs. 5-6), ammonium-N concentrations and net ammonification rates varied among plantation ages. Very low ammonification rates or immobilization of N were observed in the oldest plantation, even in the laboratory incubated cores. At first glance, and when compared with the two younger areas, this would appear to indicate an inhibition (such as by allelochemicals) unique

to the old stand. But when total ammonium-N concentrations were studied, at the end of the incubation period all the sites had similar concentrations, although initial concentrations varied by a factor of 2. These results suggest that:

1) In the old stand, ammonium-N production occurred earlier in the summer and that uptake and/or losses were low so that, even with no further ammonification, final N concentrations were similar to the younger stands.
2) Once a certain level of ammonium-N was reached, further ammonification ceased. This may be related to limitations in the availability of C or some other nutrient.
3) Initial ammonium-N levels in the younger stands were lower than the old stand. This may be related to higher N losses through leaching (Morris, 1981), greater uptake rates earlier in the summer, or greater nitrification in these areas.

The clearcut area and the 9-year-old site behaved very similarly, although the 9-year-old plantation had slightly higher net ammonification rates and lower initial concentrations. For these two areas, maximum average ammonification rates were about 9.4 mg N/kg-mo (9.1 kg N/ha-mo), and average soil NH_4-N concentrations were less than 15 mg N/kg (16.5 N kg/ha).

It is important to note that the clearcut area was part of the 29-year-old plantation before the area was harvested in March 1983, only three months before the current experiments were established. Nonetheless, net ammonification rates were 3-8 times higher in the clearcut when compared with the undisturbed stand. Although initial concentrations of ammonium-N were slightly lower in the clearcut area,

which may have had some effect, the intact stand appears to exert some control over the mineralization process, directly through accumulation of toxins or greater nutrient competition, or indirectly through microclimatic or hydrologic changes (Vitousek et al., 1979, Vitousek and Melillo, 1979, Morris, 1981; Matson and Vitousek, 1981). Burger (1979) and Morris (1981) also found increases in N mineralization rates in similar sites after clearcutting, which were directly related to intensity of site preparation.

It has been suggested that N losses may be low in disturbed areas due to rapid incorporation of inorganic N into decomposing organic matter, especially in infertile areas (Vitousek, 1981; Pritchett and Morris, 1982). However, on the average, I observed no net N immobilization in any of the incubated cores from the clearcut area, which may indicate that significant losses of N can occur. In this respect, Morris (1981) reported increases in inorganic N concentrations in lysimeter solution collections in the disturbed areas he examined, which, in the absence of vegetation, may indicate N losses to the ecosystem.

In the fall, no statistically significant differences were observed among plantations for either initial concentrations of NH_4-N or net ammonification rates. But in the spring (Fig. 8) a significant interaction with plantation age was again observed. During the spring, reduced concentrations and ammonification rates were detected in the clearcut area. As suggested by Stone and Fisher (1963), this may have been due to the absence of conifers in the area, which apparently can lead to stimulation of mineralization (see also Heng

and Goh, 1984). Also a year after the harvest, less favorable conditions would exist for microbial activity, such as an increase of detritus with higher wood content, less available availability of essential nutrients, or reduced amount of labile organic N (Reiners, 1981) This could lead a reduction in available ammonium-N (there is also some indication that nitrification rates increased in the spring as will be discussed later).

In addition, it is important to note that during the fall and spring seasons, cores collected from the old stand and incubated in the laboratory, showed relatively very high rates of ammonification when compared with summer (Figs. 8 and 11). Initial concentrations were low in both cases, which reinforces the idea that ammonification rate may depend on ambient ammonium-N levels prior to incubation.

In general, all areas tended to have similar ammonium-N concentrations at the end of the incubation period, that is, ammonification rates tended to maintain a certain level of ammonium-N in the soil (10-15 mg N/kg). The differences in plantation age and degree of disturbance, therefore, were apparently insufficient to produce major changes in this nitrogen process during the year investigated. In some respects, it is surprising that, in spite of the drastic differences in soil temperature, soil moisture content, vegetation structure, forest floor organic matter, and possibly nutrient availability after the stand was harvested (see Pritchett and Morris, 1982, Gholz, Fisher, and Pritchett, in press), no apparent immediate effect was detected But, as suggested by Boomsma (1979), these forest soils may have some resistance to alterations produced on the site, especially when the area is not intensively prepared

(Burger, 1979, Morris, 1981; Morris and Pritchett, 1982). Vitousek et al. (1979) also suggested that in some cases a lag may occur before changes in N processes and pools are detected, especially if sites are low in fertility.

Treatment Effects

Treatments also had some effect on ammonification rates in certain instances. For example, when treatments were applied in March, the burned and PK fertilized plots in the summer had lower ammonium-N and ammonification rates when compared with the control plots (Fig. 5-6). But in the fall, the burned and PK fertilized cores incubated in the laboratory showed a significant stimulation of ammonification, with the PK fertilization having a larger effect (Fig. 7), rates increased almost 3 mg N/kg-mo (3.3 kg/ha-mo) when compared with the controls. In the spring, no treatment effects were apparent.

It was expected that by burning the plots, ammonification would be stimulated due to possible increases in pH, nutrient, and energy source availability, and by the possible decrease in toxins accumulated in the forest floor (Viro, 1974, Raison, 1979; Burger, 1979). However, it now seems likely that after 8 years or more of no fires in the areas studied, one light burn was not sufficient to produce any significant changes. When several soil characteristics were analyzed in the treated plots (Appendix 2), little or no differences compared to controls were determined. Burger (1979) reported some changes in similar soils which were prescribed burned, but he also found that the effects were small and temporary, usually lasting a year or less.

Jones and Richards (1977) suggested that even small increased in pH after a burn may reduce fungal populations in coniferous forests leading to reduced N immobilization, and Christensen (1973) reported a general increased in N mineralization in a California chaparral ecosystem after burning. Other investigators have also indicated such a stimulation (see review by Ralson, 1979). On the other hand, Wells (1971) and Vire (1974), for example, have reported negative effects of prescribed burning on N mineralization. Decreases may be related to a drop in the size of soil N pools because N volatilization, or to adverse effects of the fire on substrate quality, such as a reduction in hydrolysable forms of N in the soil (Viro, 1974, Jones and Richards, 1977, Vance and Henderson, 1984).

According to Cole and Heil (1981), P and N cycles may be interrelated due to the large energetic requirements of nitrogen processes. N processes will be controlled by availability of P. This would be especially true in P poor soils as in the present study. Munevar and Wollum (1977), Ross and Bridger (1978), and Pastor et al. (1984) found increased mineralization rates with greater availability of soil P. On the other hand, Ryan et al. (1972) and Ryan and Sims (1974) found that, in some cases, addition of phosphate reversed the process and lead to increased N immobilization due to an increase in microbial population growth.

In the present investigation, mixed results and relatively short term effects were observed when P was added. I found a reduction of net ammonification rates in the summer, a stimulation in the fall, and no apparent effect in the spring. When P was first added in the summer, microbial populations may have increased which utilized some

of the available N for their growth. In the fall, when additional P was applied, such an increase may not have occurred permitting the detection of larger levels of ammonium-N after incubation when compared with controls. Munevar and Wollum (1977) also observed that, in some instances, relatively low levels of P decreased N mineralization rates, especially in short incubation tests, but when more P was applied to the same soil the results were reversed. They concluded that in order to maximize net N mineralization rates and reduce time lags, large quantities of P were required. In the spring, I found no effect maybe due to the fact that extractable soil P also decreased (Appendix 2), which may have reduced microbial activity.

Finally, the NPK fertilized site in the 25-year-old plantation showed a very large enhancement of net ammonification in the summer and especially in the fall after the third application of fertilizer (Figs. 12-13). Even when initial ammonium-N concentrations were relatively high, average ammonium-N production was at least 10 mg N/kg-mo (11 kg N/ha-mo) in the summer, and 23 mg N/kg-mo (25 kg N/ha-mo) in the fall. A maximum rate of 36 mg N/kg-mo (about 40 kg/ha-mo) was reached in the field incubated cores in the fall. A large portion of the ammonium-N detected was trapped by the lower ion exchange resin (see Appendix 1), and may have been a result of relatively labile organic nitrogen, immobilized after the fertilization, being retransformed microbially with the aid of drying and wetting cycles.

Summer ammonification rates in the NPK site were at least 10 times higher than in the other treatments in the same plantation, but ammonium-N concentrations only differed about 2 times or less at the

end of the incubation period. On the other hand, fall ammonium-N concentrations were about 10 times larger in the NPK plots, but ammonification rates were only 2.5 larger when compared with the other treatments. In spring, ammonification rates were low, even lower than in the other treatments, but initial concentrations were still high and similar to summer levels. Also (and as discussed in Appendix 4), a significant drop in P concentrations to control levels was observed at this time, which may indicate some influence of P availability.

The results observed above for the summer and fall are in accordance with some other investigations. For example, Munevar and Wollum (1977), Popovik (1984), Adams and Attiwill (1984), and others have found increases in N mineralization after sites were fertilized with N, P, and K. They have suggested that such increases are due to a decrease in C/N ratios in the soil (see also Rosatta and Berendse, 1984) and to increases in available P for enhanced microbial growth. Furthermore, as in this case where the A horizon soil was studied, the predominance of organic matter adhered to mineral soil ("heavy fraction" organic matter, as opposed to the the "light fraction") may have contributed to increase in net N mineralization, as proposed by Sollins et al. (1984), by decreasing the availability of C to be used as an energy source by microbial organisms. In other words, the limiting factor for microbial growth was C instead of N, so that less N was immobilized (see also Rosatta and Berendse, 1984).

Incubation Method Effects

When different incubation methods were studied, several tendencies were established

1) The saturated laboratory incubated cores had the highest initial ammonium-N concentrations and ammonification rates, except in the summer for the cores collected in the 25-year-old plantation. Keeney (1980, 1982) indicated that, in general, this type of anaerobic incubations usually yields higher levels of ammonium-N than aerobic incubations, and that ammonium-N released tends to correlate well with plant uptake and growth (see also Powers, 1980). Results from my incubations suggest that in the field, when an area floods, ammonium-N may accumulate due to reduced nitrification rates, and, perhaps, reduced plant uptake

2) Unsaturated laboratory incubated cores followed similar patterns as the saturated cores, although ammonium-N concentrations tended to be lower at the end of the incubation period. Although nitrate levels were also low, as will be discussed later, some of the ammonium-N mineralized may have been nitrified and subsequently denitrified in high humidity microsites (Keeney, 1982). On the other hand, the moisture content of the soil cores may not have been optimum in all the cases, effecting the average ammonification rates obtained (see also Cassman and Munns, 1980).

3) The field incubated cores tended to behave similarly to the saturated cores in the summer. This similarity may have been due to the high humidity conditions found in the field, in several instances (at least three times during the incubation period) the sites flooded. But, in the fall and spring little or no differences were detected between the field incubated cores and the initial concentrations, although the laboratory cores showed relatively high activity. This suggests that the lower soil

temperatures compared with the summer were an important factor in regulating the N mineralization process by reducing microbial activity. There is some other evidence that this may be the case. For example, CO_2 respiration measurements made in the same area (Gholz, Ewel, Cropper, and Hendry, in press) show that evolution decreased in August-September and increased again between April-May, and was highly correlated with changes in soil temperature. In addition, other biologically-influenced, variables, such as changes in P and soluble organic carbon availability, decreased during the same periods (see Appendix 2 and 4). Tate and Meyer (1983) also found decreased soluble organic C concentrations in streamwater, during the winter from several forests in the Coweeta Basin, North Carolina.

Results from my study indicate that, although the potential to mineralize nitrogen existed all year as the laboratory incubations indicate, in situ conditions did not allow the process to occur in the fall and spring.

Finally, single physical or chemical variable measured strongly influenced ammonification rates. The most important variable were K, SOC, pN, and soil moisture content, but their ability to improve regression equations was small, the r^2 for the most complete linear model was only 0.25.

Nitrification

Nitrate concentrations in forest soils are usually low for a variety of reasons (Vitousek et al., 1982), such as low nitrification rates, rapid assimilation of NO_3-N by vegetation, and rapid losses NO_3-N through leaching and/or denitrification.

According to several workers (see review by Keeney, 1980) non-N treated forests show low nitrification rates because of the acidic conditions usually found in the soil. Burger (1979) determined that, for mature pine stands similar to those of the present investigation, a nitrification threshold for pH was around 4.5. Surface soil pH's on the present investigation areas tended to be around 4.0 (Appendix 2, Gholz, Fisher, and Pritchett, in press). Other potentially important factors include the presence of inhibitory allelochemicals (see review by Rice, 1984), or the low availability of nutrients such as ammonium-N and inorganic P (Verstraete, 1981). In addition, if ammonium-N availability is low, heterotrophic bacteria are considered to be better competitors for NH_4-N than autotrophic nitrifiers (Jones and Richards, 1977), so that nitrifiers will be outcompeted even if other environmental factors are adequate.

Plant uptake of nitrate may also lead to low nitrification. Haines (1977) and others have concluded that vegetation in early successional communities preferentially uptake nitrate, while in older communities ammonium-N is preferred. In addition, Heng and Goh (1984) observed that the coniferous forest they studied absorbed less nitrate than a nearby beech forest. On the other hand, Attiwill and Adams (1984) determined that if nitrate levels were high, nitrate reductase activity in roots of P. radiata D. Don increased.

If little plant uptake occurs, and if the soil has a low anion exchange capacity, as many forest soils do, then nitrate losses through leaching or denitrification are expected to be high.

My results indicate that very low nitrate concentrations and nitrification rates occurred in the slash pine plantations, especially

in the fall and spring (concentrations were usually less than 1.0 mg N/kg or 1.1 kg N/ha, and rates less than 0.5 mg N/kg-mo or 0.6 kg N/ha-mo). Similar results were found by Morris (1981) and Burger (1979) in sites comparable to the ones studied here. I did observe some variations in results, however, depending on treatment, plantation age, season, and incubation method.

Plantation Age Effects

Plantation age had some effect on the nitrification process, but varied depending on season. During the summer (Fig. 14-15), nitrate levels were higher in the 9-year-old plantations and the PK plots of the 29-year-old stand than in the clearcut area, but no other differences were detected. No major variations were observed in nitrification rates, although they were slightly higher in the PK plots of the 29-year-old stand. Most values were less than 0.3 kg N/ha-mo.

During the fall (Fig. 15) a small but significant increase in nitrate concentrations was found in the clearcut area, although overall nitrification rates were lower. In the spring (Fig. 17), nitrate-N concentrations and nitrification rates were greatest in the clearcut. This agrees with result of Matson and Vitousek (1981) who found that nitrification increased after an area was disturbed, although in my study it began to rise only a year after the site was harvested. Ammonium and inorganic P levels in the clearcut site were similar or lower in spring than in the other two seasons which suggests that rather than a nutritional limitation (such low available P), as indicated by Purchase (1974), Verstraete (1981), and Vitousek et al. (1982), other factors were regulating nitrification (this may

point to a decrease in allelochemical concentrations because of removal of live pine overstory as suggested by Rice and Pancholy, 1972).

As mentioned, nitrification rates were high in the clearcut in the spring, a year after the site was disturbed. This lag in response would reduce nitrogen losses allowing time for vegetation to recover (Vitousek et al., 1979), although I expect that, with higher temperatures and a still undeveloped vegetation in the summer, leaching losses would still be relatively high

In the 9-year-old stand, with a strong herbaceous understory, no differences were observed with season and were similar to results observed in the 29-year-old stand. This indicates that increases in nitrification rates which could occur after a disturbance, decrease early as stands developed

Treatment Effects

Burning and PK fertilization did not have a strong effect on nitrification. In the burned plots, no changes in soil chemical characteristics that were observed (Appendix 2) apparently had any effect on nitrification. Instead, litter N pools may have been reduced through volatilization which increased heterotrophic bacterial competition for the remaining ammonium-N substrate On the other hand, P and K availability were increased in the fertilized plots, but still, no effect on nitrification was detected, (except for a small and temporary increase in the summer in the 9- and 29-year-old plantations). Although Purchase (1974) and Pastor et al. (1984) suggested that inorganic P availability limits nitrification, in my

established stands other factors seem more important, such as low available ammonium-N or accumulated toxins.

There is some indication that when ammonium-N levels are increased, in conjuntion with adequate levels of available P, nitrification rates may increase. For example, when the 29-year-old plantation was fertilized in August with NPK (N as urea), fall incubated cores showed high concentrations of nitrate and high nitrification rates. After the one month incubation, nitrate concentrations rose 5 to 45 times, depending on incubation method, when compared with other treatments (Fig. 21), and rates increased from negative or near 0 values to a maximum of 16 mg N/kg-mo (approx. 18 kg/ha-mo) in the NPK field incubated cores (Fig. 22). These results are in accordance with those of other investigators such as Williams (1983), Robertson (1984), and Adams and Attwill (1984), who also reported increases in nitrification with added nitrogen. However, a stimulus does not always occur (Roberge and Knowles, 1966, Boomsma, 1979, Matzner et al., 1983, Popovic, 1984). Some reasons for such apparently conflicting results are that there were differences among studies in substrate quality, the type and amount of fertilizer applied, the effect of the fertilizer on pH or other soil factors, the availability of other nutrients, and the delay between the treatment application and the initiation of the studies. Boomsma's (1979) site was very similar to my sites. When he fertilized a 26-year-old slash pine plantation with urea, the soil pH increased by two units, but neither factor appeared to stimulate nitrification, indicating that perhaps low availability of P was controlling the process.

The high nitrification rates I found in the 29-year-old plantation when NPK was added, appear to confirm the hypotheses and results of Lamb (1980), Verstraete (1981), Matson and Vitousek (1981), and Robertson (1984) that nutrient availability, rather than plantation age, successional stage of the forest or the presence of a toxin, was the factor controlling this process. However, the fact that fertilization increased soil pH, and that the current site was fertilized with these chemicals three years in a row, may have reversed existing acidity and toxin inhibition effects and permitted an increase in nitrifier population growth (Gosz, 1981).

Incubation Method Effects

The results of the various incubations showed that, in general

1) Unsaturated laboratory cores tended to have the highest concentrations of nitrate-N. Concentrations were especially high in the fall and spring in the NPK fertilized cores from the 29-year-old plantation, and in the spring in the clearcut area.
2) Field incubated cores had relatively low nitrate-N concentrations, except for the NPK plots. Much of the nitrate-N from the NPK cores was trapped by the lower ion exchange resin (Appendix 1). Some undetected denitrification may also have occurred as not all the nitrate-N may have reached the resin during the 30 days and because the sites flooded several times during the incubation period, providing an environment conductive to denitrification.
3) Saturated cores also have low levels of nitrate. This was expected because nitrification ceases under such high moisture contents, and the nitrate-N present will be denitrified (Keeney, 1982). Reddy and Rao (1983) suggested that some nitrification can

still proceed as ammonium-N diffuses to microsites relatively high in oxygen. In my study though, flood water was not aerated and very acid, and available ammonium-N was low.

The drop in nitrate-N was especially pronounced in the saturated cores after the NPK fertilization at the 29-year-old stand. A negative value of 24 mg N/kg-mo (26.4 kg N/ha-mo) was obtained, representing a nitrate loss of approximately 0.9 kg/ha-day when the soil was saturated. Such a decrease in nitrate concentration did not occur in the field incubated cores for several reasons: nitrification was possible when the cores were not saturated, nitrate was leached down and trapped by the lower ion exchange resin where no further transformation occurred (Schnabel, 1983), and field cores were not under high moisture contents for much of the incubation period.

In general, a drop in nitrate concentrations and nitrification rates occurred in all the sites in the fall and spring, except in the clearcut area and the NPK plots (in the fall only). This may have resulted from a decreased in available ammonium-N and a decrease in microbial activity in these periods (as was discussed in the Ammonification section). Regression analysis showed some influence of ammonium-N concentrations on nitrate levels in the soil cores at the end of the incubation period, as well as of other factors such as pH, Al, Ca, and soil moisture content, but the overall r^2 with all factors included was equal to 0.13.

Finally, the effect of urea fertilization on nitrification was temporary. When cores were incubated in the spring, less than four months after the fall incubation, nitrate levels were very similar to those in the control plots (Fig 22)

Potential Non-Symbiotic Biological N_2 Fixation

Nitrogen inputs to forests through non-symbiotic fixation are considered to be low when compared with symbiotic fixation or when compared with total existing N pools. Nonetheless, in N stressed ecosystems, even small amounts may be important to the overall stability of the system

Forest soils are characterized by low pH's (Keeney, 1980) and this is certainly the case of many flatwood forests in Florida (Pritchett and Comerford, 1983). According to Jurgensen and Davey (1970), this condition tends to favor the development of the free-living bacteria Clostridium sp. and Bacillus sp. In addition, Brouzes et al. (1969) found that, in some Quebec forest soils, greater N_2 fixation usually occurred under anaerobic environments and that Clostridium was widely distributed in these soils. Granhall and Lindberg (1979) found that, in stands of Scots pine and in stands of mixed pine and Norway spruce, heterotrophic nitrogen fixation was mainly due to aerobic and facultative anaerobic bacteria, but was greatest in sites with high C/N ratios, relatively low O_2 tensions and less acidic conditions. O'Toole and Knowles (1973) indicated that in some sandy loam forest soils, low nitrogen fixation efficiencies of aerobic bacteria under low oxygen concentrations were caused by intense competition for energy sources and by low pH's. Lozano and Velasco (1972) have suggested that pine forests tend to inhibit the development of aerobic nitrogen bacteria while stimulating anaerobic ones.

On the other hand, Smith et al. (1982) found that in Florida agricultural soils, fixation activity was favored by high moisture

contents and low oxygen concentrations (the nitrogenase enzyme properties are destroyed in the presence of oxygen) and that Klebsiella sp. and Enterobacter sp. bacteria were the most predominant (R. Smith, pers. comm., 1984).

Other nitrogen fixing organisms, that have been associated with forest soils, include the blue-green algae (Cyanophyta) which may be of great importance in clearcut or open stand areas (Jurgensen and, Davey, 1968, Granhall and Lindberg, 1978). In addition, associative relationships, have been discovered between coniferous tree roots and N_2 fixing bacteria (Silvester and Bennett, 1972, Richards, 1973) and according to Richards (1973), Clostridium was one of the most dominant species. This condition would certainly improve the nitrogen fixation capabilities of the bacteria and the efficiency of trees to absorb the fixed N.

Non-symbiotic fixation rates reported in the literature for forests are variable. For example, Granhall and Lindberg (1978) determined values ranging from 0.35 to 38.0 kg N/ha-yr, while Todd et al. (1978) found values ranging from 12-20 kg N/ha-yr. In general, reported rates are lower than this, usually below 3-5 kg N/ha-yr (e.g. Vance et al., 1983) for different forest systems.

In my study relatively low potential nitrogen fixation rates and very high spatial variability were obtained for the A horizon (Fig. 23; Appendix 3) with a maximum average rate of 261.4 nmoles of ethylene/core-hr. This is conservatively calculated to yield approximately 5.2 kg N/ha-yr assuming this rate was constant for 6 months/year and 18 hrs/day, and with a 5:1 conversion factor (ethylene:dinitrogen fixed). This value represents one sixth of the N

uptake requirements of these systems (see Gholz, Fisher, and Pritchett, in press), average values would be between 2 and 3 kg N/ha-yr.

Stand age, treatment, and season produced mixed effects on nitrogen fixation rates with statistically strong interactions. For example, the control plots from the clearcut site showed higher rates than control plots from the other two plantations. But the burned and PK fertilized plots from the clearcut site tended to be lower than the same treated plots from the other two sites.

In the 29-year-old plantation, relatively low rates were detected in the summer and fall regardless of the treatment, but rates increased during the spring in the control and PK plots. On the other hand, the 5-year-old stand tended to have medium to high rates in all seasons when compared with the other two sites.

Higher acetylene reduction activity in the clearcut site may have been related in part to higher temperatures, higher moisture contents, higher availability of C sources, and higher light intensities near the soil surface when compared with the older stand. Some of these conditions may have favored free-living nitrogen fixing bacteria as well as blue-green algae (Jurgensen and Davey, 1968, Grenhell and Lindberg, 1976), although no evidence of algal crusts were observed. In addition, the presence of grasses, especially in the spring, may have positively influenced potential nitrogen fixation rates. Smith et al. (1982) found that highest activity was associated with high amounts of grass-roots, with Paspalum notatum (Flugge) as the most prevalent species, and that cores with no roots showed very low activity (R. Smith, pers. comm., 1984).

Treatments also yielded different tendencies depending on the season and plantation age (Fig. 23). In the clearcut, both burned and PK fertilized plots tended to have lower rates than the controls in all the seasons, except in the spring where activity in the burned plots increased. But, in the 9-year-old plantation, these two treatments (i.e. burned and PK fertilization) tended to stimulate fixation, especially in the PK fertilized plots. Finally, in the 29-year-old plantation, treatments tended not to be very different from the control plots during the summer and fall, although the burned plots had slightly higher averages. In the spring, PK plots activity increased dramatically, but burned plots tended to have similar values as before. Control plots also showed an increase in potential nitrogen fixation activity in the spring, but rates were not as high as the PK plots.

On the NPK fertilized site, consistently lower potential nitrogen fixation rates were observed in all seasons when compared with the other treatments in the 29-year-old plantation. Nitrogen fertilizer additions probably inhibited potential N_2 fixation activity, as reported by Lundgren (1979), van Kessel and Roskosky (1983), and others. Also lower soil moisture contents tended to occur in this plot (see Appendix 3), which may have lead to lower activity.

In the literature, various effects of treatments have been reported. Jorgensen and Wells (1971) were some of the first investigators to observe that prescribed burning may stimulate nitrogen fixation activity (in a loblolly pine plantation in S Carolina). They suggested that such an increased was attributable to the release of nutrients, to lower acidity levels, and to an increase

in light penetration after the fire. They also found high spatial variability (only 14% of the samples showed higher activity in the burned plots) and suggested that this was related to the non-uniformity of the burn. Other studies (Fowells and Stefenson, 1934, Isaac and Hopkins, 1937, Lunt, 1961, as reviewed by Raison, 1979) detected increases in Azotobacter and Clostridium populations after burning. However, other investigators have not found such a stimulus after burning (e.g Jorgensan, 1975, Vance et al., 1983) which indicates that other factors must be considered when evaluating this effect on nitrogen fixation activity.

Similar mixed results have been found on the effect of P additions on nitrogen fixation, although little work has been done with non-symbiotic organisms. According to Griffith (1978, as review by Cole and Heil, 1981), due to the high energy requirements of the nitrogen fixation process, P availability can control root infection, growth, multiplication, and activity levels of nodules and bacteria in the rhizosphere. Van Kessel and Roskoski (1983) determined increases in activity (acetylene reduction) in leguminous nodules when P was added, but the stimulus depended on P concentration and age of the plant. Ludgren (1978) found at least a 10-fold increase in non-symbiotic fixation rates in a P fertilized lake, and Silvester (1978) reported a stimulus in activity in the decomposing humus layer of a New Zealand forest after P levels were increased. On the other hand, Jonas (1979) failed to improve fixation rates of indigenous nitrogen fixers in a coniferous forest when he added phosphates alone or in combination with other nutrients.

Time of the year had a relatively strong influence on the nitrogen fixation rates I found. This also has been reported in other studies (see, for example Vance et al , 1983, Boring and Swank, in press). In general, the highest rates occurred in the summer and spring with a relatively large decrease in the fall. Spacially high values were detected in the spring, but variability was also higher then in the other seasons.

Several stepwise linear regressions and correlations were performed using the logarithmically transformed ethylene production data to try to link acetylene reduction to variation in several soil chemical and physical characteristics (Appendix 3). Results showed very low r^2 values (0 29) even when several factors were included in the model The complete model was:

$$LAR = 1.4 - 0.02\ K - 0.20\ OM + 0.05\ MC + 0.06\ Zn$$

where LAR is the log. transformed value of ethylene produced in the core, K is potassium (mg/kg), OM is organic matter (%), MC is moisture content of soil (%), and Zn is zinc (mg/kg) Smith et al. (1982) also found positive relationships with MC and Zn, although the above model disagrees with the work of Smith et al. in that OM and K did not appear in their model. In addition, they found that calcium concentrations had some affect.

In summary, mixed results were obtained when potential fixation rates were compared among treatment, plantation age, and season, but, in general, low rates were observed in all cases regardless of the treatment applied or plantation age. Rates tended to decrease with season. In addition, very high spatial variability was observed which

suggests that very specific conditions or factors must interact to yield the higher levels of fixation

In addition to the soil core study, I performed several preliminary tests on decomposing wood collected from the 29-year-old stand They indicated that potential nitrogen fixation activity may be high in certain microsites (Table 6), and may even be higher per ha than in the surface mineral soil From 4.4 to 10.3 Kg N/ha-yr were potentially fixed assuming the forest floor was covered completely with this type of wood and using the same assumptions as above However, because large wood pieces cover only about 1% of the ground area, actual values would be less than 0.1 kg N/ha-yr A similar study on the litter layer alone was also made, but very low rates, about 0.1 kg N/ha-yr, were detected

N Uptake by Vegetation

Decreased availability of N and/or P is one of the causes for an early cessation of plantation growth (Pritchett and Comerford, 1983; Gholz and Fisher, in press; Gholz, Fisher, and Pritchett, in press). In this section, different sources and sinks for N will be discussed and compared to vegetation uptake.

By definition, the total net mineralization rate is equal to the difference between the total amount of inorganic N at the end of the incubation minus the total amount at the beginning of the incubation. When nitrification in the core is possible (e.g. in aerobic incubations) nitrate concentration changes also need to be considered.

Based on the field and laboratory incubation results, and if it is assumed that there were between 4 and 6 months of significant activity (no mineralization occurred in the field incubated cores

during the fall and spring) and an average ammonification rate of 5-10 mg N/kg-mo (5-10 mg N/kg-mo), 24 to 66 kg N/ha-yr were ammonified during the year which could have been absorbed by vegetation, nitrified, or lost through leaching.

According to estimates by Gholz, Fisher, and Pritchett (in press) in the same or similar study areas, annual soil N uptake rates of vegetation ranged from 41 kg/ha-yr in an 8-year-old plantation, to 30 kg/ha in a 26-year-old plantation. In their study, it was suggested that mineralization processes in these poor sites and the small atmospheric inputs are not able to compensate for decrease availability of nutrients, especially N and P, over time, leading to cessation of biomass increments around 25 years. But, at least in the case of N, the net N mineralization rates calculated in this investigation, indicate that supplies of N are borderline adequate for stand growth, especially in the young plantations. Nutrient requirements in young stands are greater due to the rapid growth rates and because vegetation is more dependant on availability in the soil rather than on internal recycling, in contrast to older stands more dominated by pines (Gholz, Fisher, and Pritchett, in press). But it is also important to note that only 20% or less of the total inorganic N found in the field cores was trapped by the bottom ion exchange resin (Appendix 1), which may indicate that mass flow of N to roots may be a limiting factor.

In older plantations, the forest floor is an active sink for nutrients, especially of N and P (Millar et al. 1979; Gholz, Perry, Cropper, and Hendry, in press; Gholz, Fisher, and Pritchett, in press), and as the litter layer apparently continues to accumulate in

the absence of burning these nutrients will not become available for some time. Also mineralization rates are usually greatly reduced with depth in the mineral soil (see Cassman and Munns, 1980) which suggests that vegetation may be very dependant on mineralization taking place in the surface mineral soil for their N requirements. Additional N sources for plant uptake include throughfall solution, non-symbiotic N_2 fixation. According to Gholz, Fisher, and Pritchett (in press), throughfall may contribute approximately 10 kg inorganic N/ha-yr which can reach the mineral soil. By itself, this amount will not be enough to satisfy the plantation uptake rates but will reduce the dependence on net mineralization rates. Values for the 8- and 26-year-old plantations were similar.

Another possible N input is non-symbiotic nitrogen fixation. According to the results I obtained, average rates were below 3 kg N/ha-yr. This is a very small contribution to the total N uptake of the vegetation, but could be important in building the N pools of the ecosystem over a rotation. In addition, point sources of nitrogen fixation in decomposing wood may be important, although rates are limited by the relative scarcity of dead wood in plantation.

A diagrammatic summary of estimated nitrogen fluxes for an unfertilized 29-year-old plantation is presented in Fig. 24. Similar fluxes occur in the other two sites, except that in the clearcut area there is less vegetation uptake and, as a consequence, N outputs may increase, and in the 8-year-old stand that vegetation uptake is somewhat higher (around 40 kg N/ha-yr). According to my calculations, vegetation uptake and available N are nearly balanced in the two older plantations, reducing solution N losses from the ecosystem (Morris and

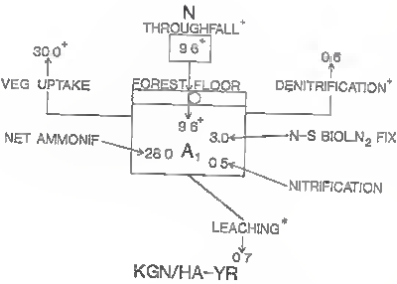


Figure 24. Nitrogen fluxes (kg N/kg-yr) for an unfertilized 28-yr-old slash pine plantation (* from Morris and Pritchett, 1982, and from +Gholz, Fisher, and Pritchett, in press)

Pritchett, 1982). On the other hand, the recent clearcut area had similar mineralization rates as the above areas with no evidence of N immobilization, suggesting that, because little or no vegetation was established during the study, there is a high probability that N was lost from the system which reduced N storages for developing plantations and highlighting the importance of other N inputs over the subsequent rotation. The vegetation on these sites may be adapted to ambient N mineralization rates with growth patterns adjusted to reduce requirements. Pines, including slash pine, are adapted to infertile sites (Switzer and Nelson, 1972, Miller et al., 1979, Pritchett and Comerford, 1983) and the following mechanisms have been suggested that enable coniferous species to survive under these conditions:

1) Pines have low nutrient requirements as indicated by low nutrient levels found in the tree tissues.
2) Nutrients are cycled efficiently, losses from the ecosystem are minimal.
3) Nutrient inputs are effectively retained through immobilization in the forest floor or vegetation components.
4) Pines are able to internally recycle nutrients reducing their dependence to soil available.
5) Pines have special adaptations, such as mycorrhizal associations, which enable the pine trees to obtain otherwise unavailable nutrients.

Due to these adaptations, not all plant species adapted to infertile soils are able to increase their growth rates when available of nutrients increases. For example, Chapin (1983) found that certain taiga tree species tended to accumulate nutrients without

increasing biomass production when the availability of nutrients increased. In addition, some of the adaptations to infertile conditions may not be eliminated and may become a disadvantage when fertility increases, such as the case of the mycorrhizal association. In slash pine trees, growth responses to increased nutrient availability have been well-documented (e.g. Fisher and Garbett, 1980), although the degree of response depends on age and soil characteristics of the stand. This suggests that slash pine, although adapted to poor soil environments, can adjust physiologically to take advantage of nutrient increases.

Very low levels of nitrate predominated in my plots not fertilized with N, and with few exceptions, nitrification rates were around 0.5 mg N/kg-mo or less, suggesting that ammonium-N may be the main N species absorbed by vegetation. But nitrification was high in the NPK plot in the fall, adding a significant amount to the total N accumulated during the incubations (Table 7). As much as 52 mg N/kg-mo (57.2 kg N/ha-mo) total net mineralization was observed in the field incubated cores on this site, 31% of which was nitrate. This high value in the field cores when compared with the laboratory cores, may have been a result of drying and wetting cycles which helped mineralize labile organic N (Birch, 1959, Sahrawat, 1980) and, under unsaturated conditions, nitrification was possible. Denitrification losses of nitrate were most likely prevented or greatly reduced by the ability of the ion exchange resin to trap and preserve nitrate. Analysis of bottom resins (Appendix 1) also showed that the potential for nitrate to leach was high if vegetation uptake for this N ionic species is low. The unsaturated laboratory cores showed a positive

Table 7. Net changes in soil N concentrations (mg N/kg) after a 30-day incubation in the 25-yr-old plantation for the NPK treated plot during the fall, and for the various incubation methods.

	INCUBATION METHOD		
	Field	Unsat.	Sat.
NH_4-N	36.3	-8.0	23.1
NO_3-N	15.9	9.0	-24.2
Total N	52.2	1.0	-1.1

balance of only 1 mg N/kg-mo (1.1 kg/ha-mo). Apparently a portion of the ammonium-N was nitrified or immobilized as values tended to be smaller than initial concentrations. If the N ammonification rates were similar to the saturated or field cores, and ammonium-N nitrified, then a part of the nitrate formed could have reached high humidity microsites inside the cores where it was denitrified (there is some indication that denitrification is possible as suggested by the saturated laboratory results, Table 7).

If it is assumed that the total net mineralization of 57.2 kg N/ha-mo from the NPK field cores in the fall was constant from August, when site was fertilized, to November, when the incubation was performed, an estimated N production of 229.9 kg N/ha occurred. This value represents about 9 times more N than the vegetation can possibly absorb, so that about 200 kg N/ha may be available for other ecosystem processes or for leaching.

SUMMARY AND CONCLUSIONS

Seasonal ammonification, nitrification, and potential non-symbiotic nitrogen fixation were monitored in an age sequence of slash pine plantations (0-,9-, and 29-yr-old) in order to evaluate the effects of burning, PK and NPK (29-yr-old plantation only) fertilization, and plantation age. In addition, water soluble organic carbon, double acid extractable P, and other soil variables were measured to determine if relationships with the above processes existed. Laboratory, unsaturated (aerobic) and saturated (anaerobic), and field incubated undisturbed A soil cores were used to assess ammonification and nitrification rates. The field incubation consisted of a new method in which both ends of intact cores were covered with a nylon-mesh bag containing an ion exchange resin. This improved diffusion of gasses from and into the core, permitted changes in moisture content during the incubation period, and avoided concentration buildups of nutrients in the soil solution (simulating in part, uptake by vegetation) as they moved down and were trapped by the resin. Biological nitrogen fixation was determined using the acetylene reduction method

Results obtained from this investigation lead to the following conclusions

1) Ammonium-N concentrations (10-15 mg N/kg) were similar in all sites not fertilized with N at the end of the 30-day incubation period regardless of the initial concentrations.

2) Ammonification rates apparently were affected by initial NH_4-N at the beginning of the incubation. If ammonium-N levels were low, ammonification rates were high; in the majority of the cases rates ranged between 5-10 mg N/kg-mo for the laboratory incubated cores and field incubated cores in the summer.

3) Nitrate concentrations and nitrification rates were low in all plantations (less than 1.0 mg N/kg and less than 0.5 mg N/kg-mo, respectively).

4) Nitrogen concentrations and ammonification and nitrification rates decreased in the fall and spring when compared with the summer.

5) In the recent clearcut no indication of net N immobilization was detected and little or no vegetation was present at the time. These factors suggest that higher leaching losses would be expected to occur in this site.

6) Nitrification rates in the unsaturated laboratory cores increased in the recent clearcut area one year after the harvest to a least an order of magnitude higher than in other areas. Ammonium-N and inorganic P levels in the clearcut were the same or even lower than in the older plantation, suggesting that nitrification was inhibited in some manner prior to the harvest. This again indicates that losses through leaching and denitrification may increase after cutting.

7) Ammonification rates were low in the 25-year-old plantation during the summer as determined by all the incubation techniques, but were similar to the other sites during the fall and spring in the laboratory incubated cores. This apparently was related to higher

initial ammonium-N contents in the summer rather than to other factors related to the presence of the intact stand.

8) Burning had little effect on ammonification or nitrification. A slight and temporary decrease in ammonification was observed in the summer on all sites, less than 3 months after the fire (especially in the 29-year-old plantation). Such a decrease may have been related to an increase in microbial growth or to a decrease in labile organic N available for mineralization.

9) PK fertilization alone had little effect on ammonification and nitrification, although a slight stimulation in ammonification occurred during the fall in the laboratory incubated cores.

10) NPK fertilization significantly stimulated ammonification and nitrification in the 29-year-old plantation. This suggests that all three nutrients are required for these processes to occur at near potential rates, although some other factors, such as changes in soil pH and physiology of the vegetation after fertilization, may also have contributed. This stimulation was temporary: less than a year after the fertilization, ammonification and nitrification rates returned to control levels.

11) Saturated (anaerobic) laboratory cores exhibited the highest net ammonification rates, followed by the unsaturated and field cores.

12) High denitrification rates apparently occurred in the saturated cores during the fall in the NPK fertilized plot, as around 90% of the nitrate present prior to the incubation disappeared. Some

non-assimilatory reduction of nitrate to ammonium also may have occurred

13) Nitrogen concentrations and mineralization rates in the field incubated cores were similar to those found in the saturated cores during the summer, but decreased sharply in the fall and spring. This suggests that field cores were sensitive to on site conditions, mainly due to decreased winter soil temperature, and that drying and wetting cycles in the cores did not apparently produce a strong increase in available N. Very moist, and often saturated, conditions predominated during the incubation period which may have overshadowed the effect of drying-wetting cycles.

14) Water soluble organic carbon and extractable P concentrations apparently did not affect N mineralization or nitrification, suggesting that quality and not quantity of soluble C, and low availability of N in these sites may be the limiting factors.

15) Very low non-symbiotic N_2 fixation rates and high variability were observed.

16) Higher biological N_2 fixation rates were detected in the clearcut perhaps related to higher surface soil moisture contents, higher temperatures and higher light intensities observed in this area.

17) Nitrogen biological fixation could contribute less than 10% to the N uptake of the vegetation

18) In the NPK fertilized site, consistently low biological N_2 fixation rates were observed, perhaps related to relatively high N concentrations in this site

19) Nitrogen biological fixation rates decreased during the fall but increased during the spring relative to the summer

20) Nitrogen uptake rates for the 9- and 23-year-old plantations appear to be in equilibrium with the N mineralization rates observed and to other possible available N sources (e.g. throughfall or biological nitrogen fixation inputs). This suggests that N losses in these sites is minimal. On the other hand, in the clearcut site, losses are expected to be high

APPENDIX 1

TOTAL INORGANIC N AND P CONCENTRATIONS IN THE FIELD AND SATURATED LABORATORY INCUBATED CORES

Introduction

In this section, results from the field and laboratory saturated cores will be detailed. Data presented in the main text for the field and saturated incubation techniques represented the sum of N and P concentrations found in both the soil and bottom ion exchange resin (IER) extraction or drained water solution, respectively.

Only the bottom IER was analyzed. It was assumed that the leachable N and P fraction moved down as rainfall water percolated through the core, before the area flooded. If the site floods, addition of an extra ring with IER at both ends of the core would improve the method and would eliminate the need for these assumptions.

Some N and P may be desorbed from the soil exchange sites when the core is saturated with water (see Reddy and Rao, 1983). If the water contains sufficient oxygen, part of the NH_4-N may be nitrified and lost later by denitrification. In the present investigation, little transformations were expected to occur, as diffusion of NH_4-N is very low, pH's were acidic (4.0 or lower), and water was not aerated. In addition, in the saturated incubations water levels were about 1.5 to 2.0 cm above the soil surface and the top portion of the cores were covered with a perforated plastic layer to reduce ventilation.

Methods

After the 30-day incubation, the soil portion of the field and saturated laboratory incubated cores were analyzed as described. In addition to the soil analyses, the excess water from the saturated cores was drained for 20 to 30 min until no more drops were seen. Solutions were then filtered with Whatman #42 filter paper, brought to a constant volume, and acidified with concentrated HCl before storage at 0° C. Analysis was performed 3 to 5 days after, except in the summer phase where it took longer. Inorganic N and P were analyzed using the Technicon Autoanalyzer II.

Bottom IER's from the field cores were air-dried to a constant weight, which took about 4 to 5 days. Each entire IER in the nylon-mesh bag was then weighed and 2 g mixed with 50 ml 2N KCl for 1 hr. The mixture was filtered with a Whatman # 42 filter paper and analyzed with the Technicon Autoanalyzer II for inorganic N and P as described.

Each bag contained one and a half tablespoons of moist IER (2 spoons in the NPK fertilized site) which yielded a 1 cm thickness when placed in the core with the ring. Moisture contents of the IER in the flask were approximately 55%, so 7-9 g of dry IER/ring were used. Total exchange capacity of the resin is 1.88 meq/g (dry basis), thus 13-15 meq/ring were available to trap nutrients from the percolating water. Very rich soil solutions range from 1-2 meq/l (K. Cromack, personal comm., 1982), so each IER bag was able to handle at least 6 liters of a "rich" solution. For the present study, the amount of resin/ring was well in excess to assure maximum effectiveness in trapping the nutrients percolating through in solution for the 30-day incubation period.

Results and Discussion

Field Incubation

Results from the field incubation are presented in Tables A1.2-A1.3 for the NH_4-N, NO_3-N, and inorganic P.

A higher proportion of NH_4-N was trapped in the IER rings from the clearcut area (23-43%) than in the other areas in the summer season (Table A1.1). In the fall and spring, the 9-year-old site tended to have highest values.

No indication of any treatment effect was observed, except in the NPK plots where about 50% of the total ammonium-N was trapped by the IER. This suggests that the potential of N leaching out of the surface soil is high.

Very low concentrations of nitrate were observed in all unfertilized sites and seasons (Table A1.2). As a consequence, little nitrate was extracted from the IER. No effect of treatment was detected, except again in the NPK site where concentrations rose dramatically after the August 1983 fertilization. About 90% of the total NO_3-N found at that time was extracted from the IER. High rates of leaching are expected if this nitrate-N is not absorbed by vegetation or denitrified, and the high amounts found in the lower resin bag reflects the poor ability of these sandy soils to retain mobile ions.

Inorganic P trapped by the IER (Table A1.3) ranged from 0 to 10% of the total in the non-fertilized plots. But this value rose to a maximum of 75% when P was added to the site. Again, these results indicate the low retention capacity of the soil and the high probability of P losses through leaching if conditions are not

Table A1.1. Seasonal NH_4-N concentrations (mg/kg) in the soil ([]s), and bottom ion exchange resin ([]r), from the various plantation ages and treatments (C = control, B = burned, and PK and NPK fertilized).

CLEARCUT (0-YR-OLD)

		SUMMER				FALL				SPRING			
TR		[]T[1]	[]s	[]r	%[2]	[]T	[]s	[]r	%	[]T	[]s	[]r	%
C	x	14.4	8.5	5.9	41.0	6.6	5.5	1.1	16.7	5.0	4.9	0.1	2.0
	SD	10.0	4.6			6.4	5.4			2.7	2.6		
B	x	13.0	10.0	3.0	23.1	4.3	3.3	1.0	23.3	3.6	3.4	0.2	5.6
	SD	3.4	3.4			2.0	1.0			0.4	0.2		
PK	x	10.8	6.2	4.6	42.6	5.6	4.3	1.3	23.2	4.6	4.3	0.3	6.5
	SD	5.1	1.7			1.3	1.3			1.3	1.2		

9-YR-OLD PLANTATION

		SUMMER				FALL				SPRING			
TR		[]T	[]s	[]r	%	[]T	[]s	[]r	%	[]T	[]s	[]r	%
C	x	12.4	11.4	1.0	8.1	5.0	4.0	1.0	20.0	4.3	3.8	0.5	11.6
	SD	4.1	4.1			1.3	1.3			2.4	2.2		
B	x	10.1	8.5	1.6	15.8	2.6	2.2	0.4	15.4	3.4	3.2	0.2	5.9
	SD	0.6	1.9			1.5	1.3			1.6	1.6		
PK	x	10.9	9.3	1.6	14.7	4.7	3.2	1.5	31.9	4.0	3.9	0.1	2.5
	SD	5.4	5.1			2.9	1.5			0.5	0.6		

29-YR-OLD PLANTATION

		SUMMER				FALL				SPRING			
TR		[]T	[]s	[]r	%	[]T	[]s	[]r	%	[]T	[]s	[]r	%
C	x	10.8	8.5	2.3	21.3	3.0	3.0	0.0	0.0	3.1	3.1	0.0	0.0
	SD	8.4	5.3			0.4	0.4			1.4	1.3		
B	x	10.1	9.2	0.9	8.9	4.1	3.9	0.2	4.9	3.8	3.7	0.1	2.6
	SD	0.6	0.5			1.1	0.9			1.1	1.1		
PK	x	10.4	8.7	1.7	16.3	4.7	4.1	0.6	12.8	4.2	4.1	0.1	2.4
	SD	3.2	3.3			0.9	0.6			0.7	0.8		
NPK	x	17.5	9.5	8.0	45.7	67.0	43.3	43.7	50.2	12.6	6.0	6.6	52.4
	SD	7.1	2.1			50.7	36.0			4.1	2.9		

[1] []T = []s + []r

[2] % = percent from total trapped in the ion exchange resin.

Table A1 2. Seasonal NO_3-N concentrations (mg/kg) in the soil ([]s), and bottom ion exchange resin ([]r), from the plantation ages and treatments (C = control, B = burned, and PK and NPK fertilized).

CLEARCUT (0-YR-OLD)

TR		SUMMER []T[1]	[]s	[]r	%[2]	FALL []T	[]s	[]r	%	SPRING []T	[]s	[]r	%
C	x	0.8	0.8	0.0	0.0	0.6	0.6	0.0	0.0	0.4	0.4	0.0	0.0
	SD	0.1	0.2			0.2	0.2			0.2	0.1		
B	x	1.0	0.9	0.1	10.0	0.6	0.5	0.1	16.7	0.8	0.8	0.0	0.0
	SD	0.2	0.1			0.2	0.2			0.5	0.5		
PK	x	0.8	0.8	0.0	0.0	0.7	0.7	0.0	0.0	0.7	0.7	0.0	0.0
	SD	0.1	0.1			0.1	0.1			0.3	0.3		

5-YR-OLD PLANTATION

TR		SUMMER []T	[]s	[]r	%	FALL []T	[]s	[]r	%	SPRING []T	[]s	[]r	%
C	x	1.2	1.2	0.0	0.0	0.7	0.6	0.1	14.3	0.3	0.3	0.0	0.0
	SD	0.0	0.0			0.2	0.2			0.0	0.0		
B	x	--	--	--	--	0.6	0.4	0.2	33.3	0.4	0.4	0.0	0.0
	SD	--	--			0.1	0.1			0.1	0.1		
PK	x	1.2	1.1	0.1	8.3	0.7	0.5	0.2	28.6	0.3	0.3	0.0	0.0
	SD	0.0	0.2			0.2	0.1			0.0	0.0		

29-YR-OLD PLANTATION

TR		SUMMER []T	[]s	[]r	%	FALL []T	[]s	[]r	%	SPRING []T	[]s	[]r	%
C	x	1.1	1.0	0.1	9.1	0.4	0.4	0.0	0.0	0.4	0.4	0.0	0.0
	SD	0.1	0.1			0.2	0.2			0.0	0.0		
B	x	1.1	1.0	0.1	9.1	0.5	0.5	0.0	0.0	0.3	0.3	0.0	0.0
	SD	0.1	0.1			0.2	0.1			0.1	0.0		
PK	x	1.6	1.2	0.4	25.0	0.4	0.4	0.0	0.0	0.4	0.4	0.0	0.0
	SD	0.4	0.4			0.2	0.1			0.1	0.1		
NPK	x	1.8	1.5	0.3	16.7	44.8	2.9	41.9	93.5	0.5	0.5	0.0	0.0
	SD	0.7	0.7			26.7	0.1			0.1	0.1		

[1&2]See notes on Table A1.1

Table A1.3. Seasonal inorganic P concentrations (mg/kg) in the soil ([]s), and bottom ion exchange resin ([]r), from the various plantation ages and treatments (C = control, B = burnad, and PK and NPK fartilizad).

CLEARCUT (0-YR-OLO)

		SUMMER				FALL				SPRING			
TR		[]T[1]	[]s	[]r	%[2]	[]T	[]s	[]r	%	[]T	[]s	[]r	%
C	x	5.2	4.8	0.4	7.7	2.2	2.1	0.1	4.5	2.9	2.8	0.1	3.4
	SD	3.9	3.5			1.0	0.8			1.2	1.0		
B	x	6.7	6.0	0.7	10.4	2.6	2.4	0.2	7.7	3.6	3.6	0.1	2.8
	SD	3.0	2.6			1.0	0.9			1.1	1.0		
PK	x	21.0	6.7	14.3	68.1	18.6	8.2	10.4	56.9	7.6	6.2	1.4	18.4
	SD	6.6	2.0			9.5	6.4			2.6	1.9		

9-YR-OLO PLANTATION

		SUMMER				FALL				SPRING			
TR		[]T	[]s	[]r	%	[]T	[]s	[]r	%	[]T	[]s	[]r	%
C	x	2.6	2.4	0.1	4.0	1.4	1.3	0.1	7.1	2.2	2.2	0.0	0.0
	SD	0.4	0.4			0.4	0.4			0.2	0.3		
B	x	4.8	4.6	0.2	4.2	1.9	1.6	0.2	11.1	2.6	2.6	0.0	0.0
	SD	1.3	1.3			0.4	0.4			0.6	0.6		
PK	x	46.8	18.4	27.4	59.8	31.3	8.0	23.3	74.4	12.8	9.4	3.4	26.7
	SD	29.3	9.5			14.1	0.7			2.9	1.8		

29-YR-OLO PLANTATION

		SUMMER				FALL				SPRING			
TR		[]T	[]s	[]r	%	[]T	[]s	[]r	%	[]T	[]s	[]r	%
C	x	4.3	4.2	0.1	2.3	2.0	2.0	0.0	0.0	2.5	2.4	0.1	4.0
	SD	0.5	0.4			0.2	0.2			0.2	0.2		
B	x	4.7	4.5	0.2	4.3	2.7	2.6	0.1	3.7	2.7	2.6	0.1	3.7
	SD	0.9	0.8			0.9	0.8			0.2	0.1		
PK	x	28.3	12.1	16.2	57.2	56.1	17.6	38.5	68.6	14.8	11.6	3.2	21.6
	SD	14.7	3.7			27.5	11.0			7.1	4.9		
NPK	x	19.5	11.0	8.5	43.6	7.3	2.5	4.8	65.8	3.7	3.1	0.6	16.2
	SD	19.4	9.2			2.4	0.7			1.8	1.4		

[1&2] See notes on Table A1.1.

appropriate for P absorption. A strong drop in concentrations was observed over time after the fertilization which may be related to the high leaching losses in previous months.

Laboratory Saturated Cores

Results from the laboratory incubated cores are shown in Tables A1.4-A1.6. In general, between 10-15% of the total NH_4-N extracted was found in the drained water regardless of plantation age, season, or treatment, except in the NPK site in the fall. In this case, about 23% of the ammonium-N was found in the solution (Table A1.4)

Nitrate values were low, as expected (Table A1.5). Nitrification does not proceed under anaerobic conditions, and nitrate present before the incubation would likely be lost through denitrification when moisture contents were increased. The potential denitrification trend was especially evident in the NPK site where a majority of the initially high fall nitrate concentrations disappeared after the 30-day incubation.

Inorganic P was also detected in the drained solution from the saturated laboratory cores (Table A1.6). Values usually ranged from 5-15% of the total amounts detected, although some exceptions were observed. Higher concentrations were detected in the solution drained from cores collected in the P fertilized area accounting for 20 to 30% of the total P found.

In general, no special trends were determined when seasons and plantation ages were compared, although field incubated cores tended to have higher concentrations in the IER than the saturated cores. This suggests that in the field, the soluble P fraction was washed out

Table A1.4. Seasonal NH_4-N concentrations (mg/kg) in the soil ([]s), and drained excess water[1]([]w), from the various plantation ages and treatments (C = control, B = burned, and PK and NPK fertilized

CLEARCUT (0-YR-OLD)

		SUMMER				FALL				SPRING			
TR		[]T[1]	[]s	[]w	%[2]	[]T	[]s	[]w	%	[]T	[]s	[]w	%
C	x	14.5	13.5	1.0	6.9	9.3	8.6	0.7	7.6	9.0	8.5	0.5	5.6
	SD	2.8	2.4			4.3	4.1			2.3	2.1		
B	x	16.8	15.5	1.3	7.7	14.9	13.0	1.9	12.8	10.7	10.0	0.7	6.5
	SD	8.0	8.1			7.0	6.2			4.8	3.6		
PK	x	13.8	12.4	1.4	10.1	13.9	12.5	1.4	10.1	10.2	9.8	0.4	3.9
	SD	3.9	3.6			6.5	6.2			3.3	2.9		

9-YR-OLD PLANTATION

		SUMMER				FALL				SPRING			
TR		[]T	[]s	[]w	%	[]T	[]s	[]w	%	[]T	[]s	[]w	%
C	x	15.5	14.9	0.6	3.9	11.3	9.1	2.2	11.5	12.4	11.4	1.0	8.1
	SD	8.1	7.4			3.6	2.6			1.8	1.4		
B	x	10.2	9.0	1.2	11.8	13.2	10.8	2.4	18.2	12.3	11.8	0.5	4.1
	SD	5.2	4.2			10.0	8.7			4.0	3.9		
PK	x	14.4	12.6	1.9	13.2	14.1	12.0	2.1	14.9	16.4	13.9	1.6	9.7
	SD	3.0	3.6			4.9	4.4			6.7	4.9		

29-YR-OLD PLANTATION

		SUMMER				FALL				SPRING			
TR		[]T	[]s	[]w	%	[]T	[]s	[]w	%	[]T	[]s	[]w	%
C	x	8.3	7.2	1.1	13.3	11.6	9.8	1.7	14.8	10.8	8.6	2.2	20.4
	SD	0.6	0.8			4.5	4.8			2.4	1.9		
B	x	7.1	7.1	0.0	0.0	11.4	10.4	1.0	8.8	10.9	9.8	1.1	10.1
	SD	3.3	3.3			4.9	4.5			2.0	1.8		
PK	x	10.3	9.0	1.3	12.6	21.0	17.2	3.8	18.1	11.1	10.5	0.6	5.4
	SD	3.6	2.7			7.5	6.0			2.9	2.9		
NPK	x	19.3	16.6	2.7	14.0	73.8	56.8	17.0	23.0	15.9	14.8	1.1	6.9
	SD	7.3	6.5			54.3	30.1			9.9	9.8		

[1] []T = []s + []w.
[2] % = percent of total found in the drained water.

Table A1 5. Seasonal NO_3-N concentrations (mg/kg) in the soil ([]s), and drained excess water ([]w), from the various plantation ages and treatments (C - control, B - burned, and PK and NPK fertilized)

CLEARCUT (0-YR-OLD)

	SUMMER				FALL				SPRING			
TR	[]T[1]	[]s	[]w	%[2]	[]T	[]s	[]w	%	[]T	[]s	[]w	%
C x	1.0	1.0	0.0	0.0	0.2	0.1	0.1	50.0	0.3	0.3	0.0	0.0
SD	0.3	0.3			0.1	0.1			0.0	0.0		
B x	0.8	0.7	0.1	12.5	0.2	0.2	0.0	0.0	0.4	0.3	0.1	25.0
SD	0.1	0.1			0.1	0.1			0.1	0.0		
PK x	0.8	0.7	0.1	12.5	0.3	0.2	0.1	33.3	0.4	0.3	0.1	25.0
SD	0.1	0.1			0.3	0.2			0.1	0.0		

9-YR-OLD PLANTATION

	SUMMER				FALL				SPRING			
TR	[]T	[]s	[]w	%	[]T	[]s	[]w	%	[]T	[]s	[]w	%
C x	0.8	0.8	0.0	0.0	0.3	0.2	0.1	33.3	0.4	0.4	0.0	0.0
SD	0.1	0.1			0.1	0.0			0.2	0.2		
B x	0.8	0.8	0.0	0.0	0.3	0.2	0.1	33.3	0.3	0.3	0.0	0.0
SD	0.0	0.0			0.2	0.1			0.1	0.1		
PK x	0.9	0.8	0.1	11.1	0.3	0.3	0.0	0.0	0.3	0.3	0.0	0.0
SD	0.2	0.1			0.1	0.1			0.0	0.0		

29-YR-OLD PLANTATION

	SUMMER				FALL				SPRING			
TR	[]T	[]s	[]w	%	[]T	[]s	[]w	%	[]T	[]s	[]w	%
C x	0.8	0.7	0.1	12.5	0.4	0.3	0.1	25.0	0.4	0.3	0.1	25.0
SD	0.1	0.0			0.1	0.2			0.1	0.0		
B x	0.7	0.7	0.0	0.0	0.4	0.3	0.1	25.0	0.4	0.3	0.1	25.0
SD	0.1	0.1			0.2	0.1			0.1	0.0		
PK x	0.8	0.8	0.0	0.0	0.4	0.4	0.0	0.0	0.4	0.4	0.0	0.0
SD	0.1	0.1			0.2	0.2			0.1	0.1		
NPK x	0.8	0.8	0.0	0.0	4.7	1.2	3.5	74.5	0.5	0.4	0.1	20.0
SD	0.1	0.1			3.5	0.8			0.1	0.1		

[1&2] See notes on Table A1.4

Table A1.6. Seasonal inorganic P concentrations (mg/kg) in the soil ([]s), and drained excess water ([]w), from the various plantation ages and treatments (C = control, B = burned, and PK and NPK fertilized).

CLEARCUT (0-YR-OLD)

	SUMMER				FALL				SPRING			
TR	[]T[1]	[]s	[]w	%[2]	[]T	[]s	[]w	%	[]T	[]s	[]w	%
C x	6.2	6.0	0.2	3.2	2.5	2.1	0.4	16.0	4.4	4.1	0.3	6.8
SD	2.1	2.2			1.1	0.4			2.2	2.1		
B x	10.0	9.2	0.8	8.0	3.5	3.1	0.4	11.4	3.7	3.2	0.5	13.5
SD	5.2	4.4			0.7	0.8			0.7	0.5		
PK x	22.8	15.2	7.6	33.3	12.9	9.4	3.5	27.1	8.7	7.6	1.1	12.6
SD	9.8	3.0			7.2	4.8			3.5	3.0		

9-YR-OLD PLANTATION

	SUMMER				FALL				SPRING			
TR	[]T	[]s	[]w	%	[]T	[]s	[]w	%	[]T	[]s	[]w	%
C x	4.1	3.9	0.2	4.9	2.2	1.9	0.3	13.6	2.5	2.1	0.4	16.0
SD	1.3	1.3			1.0	0.6			0.5	0.4		
B x	6.3	6.1	0.2	3.2	3.0	2.6	0.4	13.3	4.0	3.4	0.6	15.0
SD	3.4	3.4			1.3	0.6			1.6	1.4		
PK x	23.3	19.8	3.5	15.0	20.2	12.1	8.1	40.1	20.2	14.7	6.5	27.2
SD	17.0	14.6			9.0	4.6			13.5	8.1		

29-YR-OLD PLANTATION

	SUMMER				FALL				SPRING			
TR	[]T	[]s	[]w	%	[]T	[]s	[]w	%	[]T	[]s	[]w	%
C x	4.4	4.2	0.2	4.5	2.4	2.3	0.1	4.2	1.7	1.4	0.3	17.6
SD	0.3	0.2			0.5	0.4			0.9	0.6		
B x	5.2	5.1	0.1	1.9	3.6	2.9	0.7	19.4	2.1	1.8	0.3	14.3
SD	1.0	1.0			2.4	1.4			0.5	0.2		
PK x	28.3	23.0	5.3	18.7	50.4	33.6	16.8	33.3	16.1	12.6	3.5	21.7
SD	15.8	12.0			24.5	16.1			9.3	6.2		
NPK x	10.9	8.3	2.6	23.9	5.0	3.0	2.0	40.0	1.5	1.4	0.1	6.7
SD	4.6	3.0			1.6	1.0			0.6	0.6		

[1&2] See notes on Table A1.4.

by percolating water, preventing a possible concentration equilibration between the soil particles and the liquid phase

Conclusions

1) Relatively low amounts of N and P were detected in the lower IER bags (field cores) or the drained solution (saturated laboratory cores) for the non-fertilized plots when compared with the fertilized ones.
2) Leaching potential losses in the field are high, especially in the fertilized plots and the clearcut site.
3) Field cores showed that amounts of leachable ions are higher than in the saturated laboratory cores where solution does not move.
4) Amounts of N and P detected in the lower IER's or drained water was related to the amounts mineralized.

APPENDIX 2

SOIL SURFACE VARIABLES FOR THE N-MINERALIZATION CORES

Table A2.1. Seasonal average concentrations and standard deviations (mg/kg, except where specified) for various surface soil characteristics as determined for each of different plantation ages, treatments, and incubation methods (IC = intfiel conditions, F = field, U = unsaturated laboratory, and S = saturated laboratory cores). SOC = water soluble organic carbon, OM% = organic matter, TN = total nitrogen, MC% = moisture content.

CLEARCUT SITE (0-YR-OLD)

SUMMER

	Control				Burned				PK fertilized			
	IC	F	U	S	IC	F	U	S	IC	F	U	S
NH_4-N	7.9	14.4	10.1	14.5	9.6	13.0	10.4	16.4	6.2	10.0	8.5	13.0
	2.9	10.0	4.3	2.0	2.9	3.4	1.4	6.0	2.3	5.1	5.3	3.8
NO_3-N	0.7	0.0	1.0	1.0	0.5	1.0	0.0	0.0	0.7	0.0	0.7	0.0
	0.1	0.1	0.3	0.3	0.1	0.2	0.4	0.1	0.0	0.1	0.4	0.1
SOC	244.0	106.6	159.5	226.2	237.6	109.6	109.8	169.0	265.0	100.0	290.8	294.6
	30.1	66.4	113.6	48.0	39.4	54.4	137.0	6.1	97.0	115.0	154.0	53.7
Al	128.0	117.8	113.6	124.0	103.2	113.6	103.2	110.4	93.6	92.0	74.4	94.4
	71.6	50.3	52.2	72.5	36.5	17.1	39.5	38.4	25.7	30.2	24.1	29.5
Ca	80.0	194.4	100.0	194.0	171.2	132.0	194.0	156.0	129.6	100.0	115.2	194.4
	50.4	119.6	71.3	73.2	46.3	72.3	99.0	90.1	62.3	94.5	70.3	44.9
K	29.6	20.0	27.2	28.8	35.2	24.0	33.6	44.0	59.2	21.6	50.3	53.6
	8.8	13.4	10.3	10.4	3.4	6.3	9.2	19.1	13.7	6.0	11.5	11.5
Mg	94.4	37.6	36.4	37.6	40.8	49.6	42.4	52.0	37.6	32.8	36.8	46.4
	78.0	22.8	17.8	20.8	10.8	23.3	26.1	24.7	19.3	10.8	13.7	13.4
Mn	0.7	0.8	0.5	0.5	0.7	1.4	0.7	1.1	1.0	0.7	0.8	1.7
	0.2	0.4	0.3	0.4	0.2	1.1	0.3	0.7	0.4	0.1	0.3	0.3
OM%	3.8	3.0	5.7	4.3	4.6	3.9	5.9	3.7	3.9	3.4	7.1	4.2
	1.1	0.9	0.6	3.4	0.6	0.6	1.3	1.7	1.6	1.8	3.4	1.0
pH	4.6	4.3	4.5	4.5	4.5	4.3	4.4	4.8	4.4	4.2	4.3	4.2
	0.2	0.1	0.2	0.3	0.1	0.2	0.1	0.2	0.1	0.1	0.2	0.1
P	4.2	5.2	6.3	6.2	4.8	6.7	6.2	10.0	21.6	21.0	17.7	22.8
	1.5	3.0	3.3	2.1	0.6	3.0	2.9	5.2	9.8	6.5	8.1	9.6
TN	941.4	1133.6	874.6	893.4	898.0	1073.0	744.0	962.2	773.4	944.6	794.4	907.6
	158.7	395.6	154.5	359.1	48.0	171.6	169.6	158.0	290.2	245.5	259.0	293.0
MC%	24.2	31.0	24.1	24.6	24.6	29.0	24.1	58.1	23.8	28.8	23.4	40.3
	5.7	7.9	9.1	7.8	8.7	3.9	5.4	3.0	6.2	4.1	4.1	5.1

Table A2.1, continued.

CLEARCUT SITE (0-YR-OLD)

FALL

	Control				Burned				PK fertilized			
	IC	F	U	S	IC	F	U	S	IC	F	U	S
NH_4-N	4.3	9.9	9.1	9.3	7.1	4.3	13.9	14.9	9.2	5.0	13.1	13.9
	1.8	9.4	3.4	4.3	4.4	2.8	5.0	7.0	2.9	1.3	4.3	9.3
NO_3-N	0.7	0.5	1.8	0.2	1.1	0.9	1.9	0.2	1.2	0.7	1.3	0.3
	0.4	0.2	0.9	0.1	0.9	0.2	0.5	0.1	0.5	0.1	0.3	0.3
SOC	117.8	43.2	76.8	88.8	124.4	32.2	65.8	113.2	109.0	37.0	91.2	131.4
	51.4	20.4	23.9	29.6	21.3	10.8	22.9	22.3	37.1	19.1	21.3	62.8
Al	96.8	112.0	122.4	117.8	92.6	98.4	107.4	109.9	71.2	93.8	122.8	115.2
	51.3	73.0	68.7	54.4	35.4	76.1	92.5	81.4	22.3	44.9	78.8	32.9
Ca	82.4	81.9	101.9	98.4	91.2	71.2	123.2	149.8	132.8	129.0	206.0	183.3
	31.7	24.4	27.3	58.4	34.1	22.5	40.5	62.9	62.4	54.8	156.9	109.8
Fe	24.4	32.9	23.4	30.0	18.8	29.4	19.1	24.9	13.4	19.3	21.4	22.3
	10.7	32.8	20.3	20.1	8.9	19.7	11.1	10.9	2.2	8.2	11.3	8.3
K	19.0	12.8	16.4	19.0	14.4	13.8	23.2	18.4	40.8	20.0	42.8	36.8
	3.7	7.2	3.4	4.4	9.1	3.9	7.7	8.1	22.8	19.3	29.1	13.8
Mg	35.2	24.8	33.9	28.6	36.9	33.8	38.4	54.4	33.8	27.8	48.8	45.8
	10.0	13.6	9.7	12.3	7.7	18.4	12.2	13.4	10.4	8.2	21.1	18.2
Mn	0.8	0.3	0.3	0.9	0.3	0.9	0.7	1.0	0.9	0.9	0.9	1.1
	0.4	0.3	0.2	0.2	0.3	0.1	0.3	0.4	0.3	0.3	0.5	0.9
SWA	4.3	3.6	3.4	2.6	3.0	3.3	4.4	4.1	3.9	4.2	4.3	5.0
	0.9	0.8	0.9	0.8	1.1	0.9	1.0	1.1	0.9	2.2	1.9	2.9
pH	4.1	4.3	4.2	4.2	4.3	4.2	4.2	4.3	4.1	4.2	4.1	4.2
	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2
P	2.4	2.2	2.1	2.3	2.4	2.9	3.3	3.5	19.5	18.9	13.9	12.9
	0.9	1.0	0.9	1.1	0.9	1.0	0.2	0.7	11.0	9.3	12.1	7.2
TN	926.9	710.9	828.4	828.4	719.9	658.0	979.2	1058.8	710.0	981.3	812.4	1048.9
	220.4	214.1	423.4	154.9	156.5	170.0	248.2	341.8	222.2	380.9	329.3	497.7
MCN	24.3	23.4	27.8	32.7	23.9	20.4	20.0	40.3	20.9	23.7	27.1	36.0
	9.3	4.0	5.0	2.4	9.9	2.7	2.9	7.8	3.5	8.0	7.2	9.4
Zn	0.5	0.5	0.8	2.4	0.3	0.8	1.0	4.4	0.7	0.7	1.2	3.8
	0.1	0.2	0.2	1.2	0.2	0.3	0.1	1.9	0.3	0.1	0.4	2.4

Table A2.1., continued.

CLEARCUT SITE (0-YR-OLD)

SPRING

	Control				Burned				PK fertilized			
	IC	F	U	S	IC	F	U	S	IC	F	U	S
NH_4-N	6 1	5.0	6 4	9 0	4.6	3.6	6.0	10.7	4.7	4.6	5.0	10 2
	4 7	2.7	2 1	2.3	1.2	0.4	2.0	4.0	1.5	1.3	2 4	3 3
NO_3-N	0 4	0 4	5 6	0.3	0.3	0.0	3.7	0.4	0.4	0.7	3.0	0.4
	0.1	0.2	5 9	0.0	0.0	0.5	4.2	0.1	0.1	0.3	3.3	0 1
SOC	39 6	43 6	64 0	60 4	22.6	43.0	48.0	71.2	37.2	44.0	57 0	68 0
	27 5	23 3	20.7	31 1	10.6	10.3	19.5	16.1	19.6	20.7	23 0	54 3
Al	128 6	109 6	140 0	178 0	112.0	115.2	186.4	194.0	92.0	86 4	109 6	92 0
	60 9	61 9	72.0	70.2	48.6	44.1	41.0	26.0	36.1	26.9	49 4	54 0
Ca	158 4	100 0	110.4	136 0	127.2	121 6	116 0	129 6	102.4	99 2	112 0	136 0
	83 4	60 6	110 7	125.5	34.2	62.9	54.0	89 3	67.0	35 5	58 7	81 1
Fe	21 7	23 6	22.4	23 9	21 2	26.2	19.5	26.6	15.6	16 6	17 2	19 0
	7 4	12 2	7.9	5 0	9.3	15 9	12.1	19 3	2.9	3 6	5.5	3 6
K	26 4	17.6	18.4	22.0	24.6	17.6	19.2	20 0	32.0	24 0	26.4	30.4
	7 9	9.2	7.3	10.0	5.6	4.6	4.4	7.2	13.4	5.9	15.1	14 6
Mg	48 0	34 4	36 0	44.0	46.4	37.6	36.0	42 4	48.0	32.0	36 0	48 0
	21 7	19.3	19.9	28.7	8.7	19.5	15.7	24.4	26.4	9 1	14 1	24 6
Mn	1-1	1.0	1 0	1.0	0.7	0.9	0.6	0 0	1.5	1.0	0 9	1 2
	0.3	0 4	0.5	0 5	0 1	0.5	0.3	0 5	0 0	0 2	0 4	0.7
OM%	3 7	3.3	2.0	4.3	3.3	3.6	2.2	3 0	4.0	5 7	2 6	3-0
	1.3	0 2	1.2	3.0	0 0	0.5	1.3	0.6	1 4	0.8	2.2	1 4
pH	4 2	4 2	4.3	4 5	4.2	4 2	4 2	4.6	4.0	4.1	4 1	4.4
	0.2	0.1	0.2	0.4	0.2	0.1	0 2	0.2	0 1	0 2	0 2	0-1
P	3.0	2 5	3-0	4 4	3 7	3.6	3.2	5 7	8 5	7.6	7 1	8.7
	0.7	1 2	1 6	2 2	0 6	1.1	0 8	0 7	2 0	2.5	4 3	3.5
TN	823.4	677.0	790.8	760.2	765.4	659.2	684.2	758 0	916 6	659 6	795.0	697 2
	339-0	334.5	320.9	345.2	194 5	74.1	79 4	163 7	393 4	136 6	208.5	185 1
NC%	29.2	28.7	15.2	35 4	29 3	24.0	20 6	32 9	30 6	25.7	19.1	37.5
	6.7	9.6	5.6	10.5	6.3	1-9	5 3	5.0	9.7	2 0	6 7	10 6
Zn	0-6	0 0	1.1	22 4	0.6	1.0	1 1	21 4	0 0	1 0	1 3	28.7
	0.1	0 3	0 3	7.0	0 1	0 4	0 2	5 3	0.4	0.4	0-3	11.2

Table A2 1-, continued.

9 YR-OLD PLANTATION

SUMMER

	Control				Burned				PK fertilized			
	IC	F	U	S	IC	F	U	S	IC	F	U	S
NH_4 N	5.4	12.4	7.4	15.5	6.8	10.1	5.4	10.2	7.1	10.9	14.2	14.4
	1.4	4.1	1.1	0.1	1.3	0.6	3.2	5.2	1.0	5.5	2.1	3.0
NO_3 N	0.8	1.2	0.9	0.8	0.8	--	1.0	0.8	0.8	1.2	1.1	0.9
	0.1	0.0	0.4	0.1	0.0	--	0.6	0.0	0.1	0.0	0.7	0.2
SOC	332.4	31.6	149.8	218.5	304.2	96.6	163.0	201.6	368.6	86.0	141.8	235.8
	95.8	18.2	125.6	59.1	57.3	89.0	158.9	91.3	21.2	46.7	131.5	80.5
Al	180.8	76.8	140.0	115.2	80.0	77.6	56.0	54.4	87.2	91.2	70.4	79.2
	134.4	94.0	190.9	139.1	83.2	74.8	23.2	27.5	38.4	45.0	42.9	38.0
Ca	143.2	194.8	138.4	126.4	217.6	253.6	283.2	217.6	232.0	220.8	225.6	169.6
	96.4	68.7	100.8	82.5	34.6	83.7	63.9	102.0	110.6	37.8	61.5	69.7
K	28.8	13.6	19.2	23.2	28.8	23.2	27.2	29.6	65.6	48.8	53.6	40.8
	4.4	2.2	5.2	6.6	1.6	6.6	5.9	11.6	22.4	20.9	27.7	31.2
Mg	29.6	23.2	27.2	28.8	42.4	40.8	37.6	40.0	40.8	46.0	48.0	42.4
	13.4	10.0	15.9	16.6	18.5	18.5	15.6	15.0	10.4	16.2	23.3	25.2
Mn	1.1	1.0	0.5	0.5	2.2	2.2	1.5	1.7	1.5	1.6	1.1	1.7
	1.3	1.1	0.5	0.3	1.1	1.3	1.2	1.0	1.9	1.3	1.2	2.4
OM%	3.7	2.5	5.3	3.2	3.8	4.0	5.7	3.5	4.5	5.2	6.4	4.1
	0.7	0.7	0.2	0.4	1.5	1.4	0.8	2.0	1.0	0.8	2.6	2.5
pH	4.7	4.5	4.5	4.6	4.6	4.5	4.5	4.5	4.1	4.4	4.1	4.3
	0.3	0.2	0.3	0.3	0.1	0.2	0.2	0.3	0.1	0.2	0.2	0.2
P	2.6	2.5	3.0	4.1	3.0	4.8	5.4	6.3	29.4	45.8	33.4	23.3
	1.1	0.4	1.5	1.3	1.4	1.3	1.4	3.4	9.0	29.3	19.0	17.0
TN	828.8	782.8	991.2	944.4	827.2	1028.0	869.8	894.8	1069.2	448.2	1117.2	1185.4
	116.0	107.8	331.8	177.8	372.8	424.0	178.3	362.1	244.6	386.1	342.1	303.5
NC%	16.9	24.2	26.3	41.3	13.4	27.9	24.2	40.6	19.5	34.3	26.4	43.1
	4.4	6.3	8.5	8.8	3.0	6.1	9.3	8.3	5.2	5.6	8.2	3.2

Table A2.1., continued.

9 YR-OLD PLANTATION

FALL

	Control				Burned				PK fertilized			
	IC	F	U	S	IC	F	U	S	IC	F	U	S
NH_4-N	4.9	5.0	9.9	11.5	5.5	2.6	10.5	15.2	6.9	4.2	13.0	14.1
	1.9	1.3	3.3	5.6	1.4	1.5	8.7	10.0	2.6	2.9	5.5	4.9
NO_3-N	0.5	0.7	1.3	0.5	0.6	0.6	1.2	0.5	1.1	0.2	2.2	0.3
	0.5	0.2	0.6	0.1	0.1	0.1	0.5	0.2	0.2	0.2	2.2	0.1
SOC	88.4	53.0	52.0	140.0	108.2	44.6	65.2	162.4	108.0	36.0	38.0	145.4
	10.2	34.1	38.5	45.0	51.6	16.1	39.3	145.6	48.2	24.1	15.0	84.5
Al	104.0	96.0	188.4	111.2	56.0	62.2	89.6	92.0	50.4	52.0	64.0	86.4
	152.0	81.1	114.2	100.9	28.6	49.0	49.6	44.1	16.4	17.5	2.2	45.1
Ca	105.6	151.2	167.2	118.4	141.6	189.0	249.6	220.0	156.0	83.2	199.2	183.2
	86.2	67.5	129.0	69.5	46.1	68.1	106.0	96.0	22.9	42.0	42.9	42.1
Fe	29.2	22.1	25.6	32.5	15.5	14.0	16.3	24.2	12.3	15.0	12.0	18.2
	28.3	26.5	20.2	22.3	8.5	9.4	8.5	9.2	5.0	10.0	5.1	2.1
K	15.2	10.4	19.2	16.0	10.4	10.4	22.2	24.0	55.6	20.0	40.0	32.0
	3.3	5.4	4.4	4.0	4.6	5.6	10.4	8.0	12.0	5.2	11.0	2.2
Mg	24.0	32.0	29.6	26.4	56.0	48.6	44.0	24.0	24.0	24.0	24.0	26.4
	10.2	15.0	16.1	10.4	14.3	16.6	22.0	20.6	5.2	11.3	6.6	9.2
Mn	0.5	0.3	0.5	0.5	0.2	0.9	0.8	0.8	0.6	0.5	0.6	0.6
	0.3	0.1	0.2	0.2	0.6	0.5	0.1	0.2	0.5	0.1	0.2	0.2
OM%	4.7	5.5	4.4	3.0	4.2	2.9	4.8	4.8	4.2	5.5	4.0	5.0
	1.0	2.0	1.6	0.6	2.0	1.3	1.9	2.0	0.2	1.3	2.0	1.0
pH	4.2	4.1	4.2	4.2	4.3	4.2	4.2	4.2	4.1	4.3	4.0	4.1
	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.2
P	1.0	1.6	2.6	2.2	2.2	1.0	3.2	3.0	1.6	1.5	2.1	2.0
	0.6	0.4	0.9	1.0	0.5	0.4	0.6	1.5	0.5	1.1	0.6	0.8
TN	1050.2	1064.4	1022.8	862.8	987.0	282.4	1012.8	1234.2	855.0	222.4	886.8	1139.2
	284.2	460.1	489.3	383.2	592.0	365.4	396.2	565.2	250.8	520.5	129.9	351.8
WC%	25.4	35.8	22.2	41.8	19.9	28.3	22.6	42.9	20.0	52.5	25.8	46.6
	9.4	11.1	10.9	10.0	2.1	5.9	9.4	10.6	4.9	2.6	4.1	4.9
Zn	0.5	1.1	0.8	5.1	0.6	0.8	1.1	4.5	0.2	1.0	1.0	4.4
	0.2	0.5	0.1	1.0	0.5	0.1	0.4	1.2	0.4	0.2	0.3	1.2

Table A2.1., continued.

9 YR-OLD PLANTATION

SPRING

	Control				Burned				PK fertilized			
	IC	F	U	S	IC	F	U	S	IC	F	U	S
NH_4-N	2.1	4.2	6.2	12.4	2.5	2.6	5.6	12.2	2.2	4.0	8.8	15.4
	2.0	2.4	3.9	1.8	1.2	1.6	2.2	4.0	0.6	0.5	2.6	5.7
NO_3-N	0.2	0.3	0.6	0.4	0.2	0.5	0.5	0.3	0.2	0.2	0.5	0.3
	0.0	0.0	0.4	0.2	0.0	0.1	0.4	0.1	0.1	0.0	0.2	0.0
SOC	49.0	42.2	83.2	106.0	38.2	24.8	26.8	99.6	54.4	26.2	42.8	135.2
	21.0	26.0	47.8	38.0	10.8	22.4	23.6	41.1	25.8	22.7	38.4	41.6
Al	120.0	112.0	134.4	127.6	110.4	78.4	85.6	76.0	30.0	91.2	83.2	83.2
	158.2	182.1	198.2	177.1	106.3	62.7	87.0	56.8	47.2	27.7	48.6	27.6
Ca	124.0	131.2	124.0	125.6	271.2	184.0	186.4	231.2	287.2	280.8	164.8	191.2
	15.8	58.6	69.2	83.3	19.2	94.5	55.2	54.1	91.8	59.9	3.6	71.8
Fe	32.8	21.9	26.2	39.7	16.9	12.2	12.8	18.4	17.9	19.5	17.8	25.2
	32.6	29.3	27.1	29.4	12.9	7.8	9.2	12.2	10.4	12.6	12.9	15.2
K	20.8	28.0	19.2	17.6	30.4	20.8	21.6	25.6	49.6	26.8	21.2	40.8
	7.7	4.9	7.7	6.1	7.8	2.2	7.2	7.2	15.9	4.8	12.7	18.2
Mg	28.6	28.6	28.8	27.2	40.8	25.2	24.4	29.2	36.8	21.2	24.8	22.8
	21.7	16.1	17.8	24.1	15.9	13.1	12.8	17.8	18.9	15.3	13.1	19.4
Mn	0.7	0.8	0.5	0.7	2.7	2.9	1.2	1.9	0.6	0.8	0.8	0.8
	0.5	0.7	0.2	0.5	2.7	2.0	0.6	1.2	0.5	1.0	0.8	0.6
ORM	3.2	4.2	3.8	5.0	4.1	4.0	2.4	6.6	4.5	2.9	4.2	6.7
	1.0	1.4	1.0	2.0	1.6	0.4	1.6	2.0	1.2	1.4	1.2	2.0
pH	4.2	4.2	4.2	4.5	4.2	4.4	4.3	4.5	3.9	3.9	4.2	4.2
	0.2	0.2	0.2	0.4	0.2	0.2	0.1	0.2	0.3	0.5	0.2	0.2
P	2.1	2.2	1.5	2.5	2.2	2.6	1.0	4.0	19.7	12.8	12.2	20.2
	0.9	0.2	0.4	0.5	0.4	0.6	0.1	1.6	5.4	2.9	4.6	13.5
TN	1076.0	861.4	927.2	797.0	1054.2	776.4	841.2	1022.0	1127.0	1192.8	941.6	1214.0
	512.6	356.9	405.3	799.5	257.7	227.4	340.6	214.2	369.2	332.6	283.6	254.7
HCN	24.7	23.9	28.3	38.3	38.0	28.0	25.9	42.6	41.8	22.8	26.2	42.6
	12.7	11.1	10.7	9.1	9.4	6.2	15.2	6.2	7.5	8.3	7.5	9.2
Zn	0.6	1.4	2.2	29.5	1.1	1.2	2.2	30.3	0.7	1.2	2.6	35.7
	0.2	0.4	1.9	5.2	0.4	0.4	1.3	12.6	0.2	0.3	1.5	14.9

Table A2.1$_{11}$, continued.

29-YR-OLD PLANTATION

SUMMER

	Control				Burned				PK fertilized			
	IC	F	U	S	IC	F	U	S	IC	F	U	S
NH_4-N	7.8	10.9	7.0	6.3	1.1	10.1	9.4	7.1	9.5	10.4	7.3	10.3
	2.4	0.4	2.1	0.6	4.7	0.8	1.3	2.9	4.9	3.2	0.7	3.6
NO_3-N	0.9	1.1	1.0	0.9	0.7	1.1	0.7	0.7	0.9	1.6	1.2	0.8
	0.2	0.1	0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.4	1.1	0.1
SOC	237.0	121.4	143.2	196.0	226.6	166.4	117.6	198.0	229.2	119.2	186.6	216.4
	61.3	77.7	104.8	55.2	31.6	65.0	91.1	46.7	76.1	68.8	34.4	92.9
Al	91.2	79.2	81.6	92.0	85.6	107.2	99.2	115.2	75.2	73.6	76.0	83.2
	25.8	26.0	33.1	20.6	19.6	17.1	22.2	15.6	23.2	21.0	18.8	29.3
Ca	84.8	66.4	44.8	79.2	73.6	61.6	43.2	63.2	197.6	246.4	154.4	158.2
	48.1	29.3	18.8	33.2	52.2	31.3	35.2	23.6	143.3	283.6	190.6	131.6
K	26.0	17.6	23.2	21.6	26.4	18.4	28.0	16.4	52.8	34.4	46.4	44.0
	10.2	2.2	5.9	10.4	6.3	4.6	4.0	7.3	26.4	11.9	90.2	21.9
Mg	36.4	34.4	34.4	40.0	37.6	37.6	34.4	36.6	48.0	52.0	40.0	37.6
	11.5	7.3	17.3	20.4	13.4	17.3	14.0	9.1	32.0	38.9	90.6	18.9
Mn	0.4	0.4	0.2	0.3	0.4	0.4	0.2	0.2	0.7	1.1	0.5	0.7
	0.2	0.1	0.1	0.1	0.3	0.1	0.1	0.1	0.5	1.3	0.0	0.5
BMA	3.5	3.7	3.6	4.0	3.6	3.5	3.3	4.3	4.5	8.5	6.0	4.5
	1.3	0.6	1.6	1.0	0.9	0.6	0.9	0.4	1.7	5.4	3.1	1.7
pH	4.3	4.5	4.2	4.2	4.4	4.5	4.3	4.7	4.1	4.3	4.0	4.1
	0.3	0.2	0.2	0.3	0.2	0.1	0.7	0.2	0.3	0.2	0.2	0.2
P	3.4	4.3	4.8	4.4	4.6	4.7	5.5	5.2	23.9	28.3	23.6	20.3
	0.9	0.3	1.1	0.3	1.3	0.9	2.0	1.0	8.4	14.7	16.6	15.0
TN	1031.0	1940.6	610.2	769.4	834.0	1016.0	974.8	815.8	1079.2	1565.0	1001.6	784.0
	197.8	191.6	260.1	273.5	243.6	110.5	209.5	179.1	510.3	1130.0	547.8	228.0
NC%	17.9	32.1	20.7	42.8	14.9	29.7	22.9	43.0	21.0	90.8	25.0	39.2
	2.4	2.6	0.9	5.4	3.6	2.3	6.6	3.9	4.4	2.6	0.7	13.0

Table A2 1 , continued

29 YR-OLD PLANTATION

FALL

	Control				Burned				PK fertilized			
	IC	F	U	S	IC	F	U	S	IC	F	U	S
NH_4-N	6.0	3.0	10.1	11.5	3.6	4.1	10.4	11.4	5.6	4.7	15.1	21.0
	1.9	0.4	3.5	4.5	1.1	1.1	2.5	4.9	2.0	0.9	4.7	7.5
NO_3-N	0.3	0.4	1.4	0.6	0.5	0.5	1.3	0.6	0.7	0.4	1.2	0.4
	0.5	0.2	1.1	0.1	0.3	0.2	0.2	0.2	0.3	0.2	0.2	0.2
SOC	84.0	25.0	65.0	196.0	131.0	46.2	75.6	219.0	97.0	46.4	62.4	216.4
	18.9	19.4	16.5	55.2	23.3	26.9	41.0	65.9	31.6	25.0	28.1	92.9
Al	79.7	92.0	100.0	102.4	81.6	109.6	109.6	116.4	59.6	103.2	111.2	115.2
	33.4	38.0	49.6	32.1	27.2	42.0	49.5	44.1	23.0	9.1	16.0	26.9
Ca	56.0	64.0	107.2	82.6	62.4	78.4	104.0	89.6	124.0	131.2	140.0	164.0
	14.1	18.8	38.6	23.4	17.3	33.9	44.4	38.0	75.2	57.0	57.3	55.0
Fe	27.4	26.4	28.2	34.0	22.7	24.7	21.7	29.5	22.5	28.2	28.4	32.2
	16.4	14.8	22.4	16.9	6.5	7.3	5.2	7.8	10.0	15.7	20.0	13.4
K	18.4	13.6	27.2	20.8	16.0	17.6	24.8	23.2	45.6	32.8	46.4	50.4
	8.3	2.2	5.2	2.8	2.8	4.6	7.7	9.1	8.8	9.1	15.1	16.1
Mg	32.8	30.4	41.6	35.2	44.8	41.6	49.0	46.4	33.6	33.6	39.0	38.4
	17.8	10.0	10.4	13.1	11.9	15.9	16.8	24.0	18.2	26.5	35.9	28.4
Mn	0.2	0.3	0.4	0.4	0.3	0.4	0.3	0.5	0.5	0.7	0.5	0.7
	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.2	0.3	0.2	0.1	0.2
OM%	2.8	3.0	5.3	4.3	4.2	4.6	4.2	4.8	4.8	4.6	5.7	5.8
	0.8	0.9	1.8	1.2	1.3	0.8	0.3	2.5	1.6	1.2	2.3	2.6
pH	4.2	4.0	4.0	4.2	4.2	4.2	4.1	4.0	3.8	4.0	3.8	4.0
	0.2	0.2	0.1	0.1	0.4	0.1	0.2	0.2	0.1	0.2	0.1	0.0
P	2.5	2.0	1.2	2.4	2.6	2.7	1.6	3.0	36.4	56.1	42.4	38.4
	0.8	0.2	0.4	0.5	0.2	0.9	0.5	2.4	15.0	27.6	24.2	24.5
TN	1810.2	740.8	865.0	1081.0	973.8	875.0	1014.0	1043.0	1859.0	890.6	1037.0	1306.0
	397.2	293.0	164.8	486.7	257.4	257.2	81.5	369.2	474.0	215.6	421.7	548.6
MC%	10.6	26.3	25.3	40.5	19.1	28.2	27.6	46.1	22.9	33.6	29.8	46.1
	7.1	3.7	5.3	4.8	4.8	2.6	3.6	10.3	7.8	5.2	9.5	7.9
Zn	0.5	0.5	1.1	4.1	0.6	0.7	0.9	3.6	0.4	0.7	0.8	5.0
	0.1	0.2	0.4	3.1	0.3	0.4	0.3	1.3	0.1	0.1	0.3	1.8

Table A2.1 , continued

29 YR-OLD PLANTATION

SPRING

	Control				Burned				PK fertilised			
	IC	F	U	S	IC	F	U	S	IC	F	U	S
NH_4-N	3 5	3.1	22 5	10..8	3 4	3.6	9 7	18..9	2 0	4.2	9.1	11..1
	1.0	1 4	27 8	2..4	1 7	1.1	5.6	2 0	0 0	0 7	3.8	2 9
NOH_3-N	0 3	0 4	0 5	0..4	0..3	0 3	0 5	0 4	0 4	0..4	0 7	0..6
	0.1	0..0	0 2	0.1	0 0	0 1	0 2	0.1	0 1	0.1	0 5	0 1
SOC	67.4	23..6	65..4	159..6	202.3	27..4	33 0	134..6	54 0	14..6	45..2	108 4
	52 2	7 5	63 0	54..0	319..0	11..7	18 6	87..0	17 4	6 6	18 4	38 5
Al	109..6	83..2	84..0	85..6	112 0	104..0	82 4	92..0	100..0	107..2	96..6	100 0
	82 2	35 0	54 2	53 4	10 4	35 0	17 6	26 2	22 4	49..6	33..4	20..4
Ca	83.6	60..0	76..0	81..5	85 6	69 6	81 6	76..0	159..6	100 0	148..0	159 2
	69..0	14..8	51..5	26..4	35 3	33 0	20 6	39..1	33 7	42..0	44..5	68 7
Fe	31 0	24..0	24..0	30 0	24 6	28 6	19 0	25..7	21..7	28..2	23..7	32 7
	29.7	13..9	22 0	25 4	5 2	20 0	4..4	4..0	6 0	13..4	13..8	15 6
K	23.2	16..0	20 0	21 6	16 0	16..0	17..6	18 4	43..2	30..4	37 6	40..0
	14 5	6..6	16 3	9..2	1 0	1 0	3 6	3..6	16..6	10..4	15..1	13 6
Mg	40 6	31 2	32 0	43 2	40..0	33..6	38..4	36 0	41..6	29 6	31 2	32 0
	14..5	7..2	13 3	25..2	0..0	13 1	9..0	12..3	11 9	7 0	13 4	10 2
Mn	0 4	0..4	0..4	0 5	0..4	0 4	0..4	0 5	0 6	0..7	0 6	1..0
	0 3	0..1	0..4	0 2	0..1	0 1	0..1	0 2	0 2	0..3	0 3	0..9
BMA	3 3	4..1	1..0	5..4	3..3	4..0	1..0	4..6	4 7	5..1	1..3	5..0
	1 3	1 2	0 7	1 5	0 2	1 0	0 1	1 2	0 9	1 0	0 5	2 6
pH	4..2	4..2	4..3	4..4	4..2	4..2	4 2	4..4	3 0	4..0	4 0	4..0
	0..1	0..3	0..4	0..4	0..3	0 2	0 2	0..3	0 1	0..2	0 1	0..2
P	2.2	2..5	1..0	1 7	2 4	2 7	1..0	2..1	15 6	14 0	23..0	16..1
	0 4	0..2	0..7	0..9	0 5	0..2	0 2	0 5	11 9	7 1	20..1	9 3
TN	909..2	683..4	842 2	974..3	869..0	731 0	778 0	909 8	1322 2	841..6	1113..4	1471 4
	519..9	168 3	468..6	441 0	132 0	82 7	131 3	331..0	315 0	157 7	373 1	863..3
MCa	29 4	27 4	18 5	37..7	25 5	26 3	20 0	39 1	36..1	29..7	73 1	65 6
	11..3	3 0	9 6	6 9	2 0	1 8	4 5	5..0	7..9	2..0	3..5	5 1
Zn	0 6	0..7	1 1	33 4	0 4	0 6	1..0	26 1	1..6	6..5	1 2	34..6
	0..4	0..3	0..0	12..0	0..1	0 2	0..4	6..0	2..2	11..0	0 3	12..6

Table A2.1., continued

29-YR-OLD PLANTATION

NPK FERTILIZED

	Summer				Fall				Spring			
	IC	F	U	S	IC	F	U	S	IC	F	U	S
NH_4-N	0.4	17.5	17.2	19.3	56.7	87.0	42.7	73.0	10.7	12.6	12.7	15.9
	1.9	7.1	11.0	7.3	28.5	58.7	23.5	54.3	5.6	4.1	7.2	9.9
NO_3-N	0.0	1.0	0.9	0.0	25.9	44.0	37.9	4.7	0.0	0.5	3.3	0.5
	0.1	0.7	0.3	0.1	14.0	26.7	25.0	3.5	0.4	0.1	3.0	0.1
SOC	230.4	104.2	96.0	229.6	82.0	26.0	55.4	157.0	30.6	16.5	33.0	54.4
	31.7	78.3	45.6	109.4	11.5	17.1	21.7	111.1	19.0	13.3	26.5	49.4
Al	45.6	46.4	39.2	40.0	24.0	29.6	27.2	33.6	32.0	23.2	24.0	27.2
	11.5	14.6	8.7	10.9	5.2	5.4	3.3	6.7	12.0	7.7	9.4	10.4
Ca	73.0	117.0	65.0	63.2	59.2	68.0	62.4	88.0	140.0	110.4	78.0	88.0
	25.4	88.5	30.4	28.2	24.0	35.6	39.3	48.6	45.9	71.0	31.6	20.4
Fe	--	--	--	--	7.7	9.1	7.3	10.6	8.2	7.1	7.0	8.7
	--	--	--	--	3.1	1.4	1.3	2.6	2.0	1.0	1.9	3.0
K	32.0	20.0	24.0	24.0	53.4	49.6	49.6	38.4	44.0	20.0	42.4	39.0
	8.7	7.7	9.5	8.7	32.5	24.1	18.0	23.6	24.1	11.1	28.9	33.9
Mg	24.0	30.4	23.2	24.0	14.4	16.0	13.6	16.0	17.6	12.0	12.0	12.0
	18.1	21.3	13.7	15.3	5.4	5.9	5.4	8.0	8.1	3.3	4.0	3.3
Mn	0.4	0.7	0.3	0.3	0.2	0.3	0.2	0.3	0.5	0.6	0.4	0.4
	0.2	0.3	0.2	0.1	0.1	0.1	0.1	0.7	0.2	0.2	0.2	0.1
OM%	2.9	3.0	0.0	4.7	3.0	2.5	2.2	2.7	2.2	1.3	2.0	2.0
	0.9	0.6	2.0	2.4	0.0	0.0	0.5	0.0	0.0	0.3	0.0	0.4
pH	4.6	4.7	4.5	4.6	5.0	5.1	4.9	5.4	4.7	5.0	5.0	5.1
	0.4	0.4	0.4	0.5	0.5	0.2	0.4	0.1	0.3	0.3	0.2	0.2
P	9.5	19.5	10.0	10.9	5.0	7.3	4.0	5.0	4.9	3.7	2.4	1.5
	2.7	10.4	4.0	4.0	1.9	2.4	2.3	1.6	1.4	1.6	1.1	0.6
TN	682.4	1081.8	619.2	699.6	880.2	585.6	535.4	639.6	611.4	504.0	450.0	442.4
	216.4	355.0	246.7	217.5	365.5	217.5	160.5	179.4	173.7	63.0	77.0	114.4
MC%	18.7	31.4	21.3	36.7	13.1	25.2	16.0	35.2	24.7	24.1	18.1	33.7
	7.5	7.0	5.0	4.4	2.7	3.0	1.6	3.2	2.8	2.8	6.3	9.8
Zn	--	--	--	--	0.3	0.5	0.6	2.7	0.5	0.7	0.9	14.8
	--	--	--	--	0.1	0.1	0.1	1.3	0.1	0.2	0.3	3.4

APPENDIX 3

SURFACE SOIL VARIABLES FOR THE NON-SYMBIOTIC N FIXATION CORES

Table A3.1. Seasonal (S - summer, F - fall, and Sp - spring) average concentrations and standard deviations (mg/kg, except where specified) for various soil surface characteristics for the different plantation ages and treatments in the non-symbiotic biological nitrogen fixation soil cores. A9 = nmoles ethylene produced/core-hr (acetylene reduction, not log. transformed, see Methods), OM% = organic matter; TN = total nitrogen; MC% = moisture content.

	CLEARCUT SITE (0-yrs-old)								
	Control			Burned			PK-fertilized		
	S	F	SP	S	F	SP	S	F	SP
A9	219.2	107.1	242.4	105.0	56.3	399.0	93.7	65.0	90.3
	193.7	57.1	101.0	141.1	34.5	435.3	67.0	51.6	30.6
A1	104.0	126.4	96.0	86.4	91.2	77.6	71.2	109.6	80.8
	40.0	53.6	66.2	36.2	69.4	55.0	29.4	74.0	59.6
Ca	66.4	60.8	56.0	44.8	40.8	58.4	56.0	100.8	45.6
	47.6	50.5	40.0	18.2	16.6	25.4	65.4	120.3	10.8
Fe	--	59.4	29.7	--	35.0	26.6	--	35.7	22.6
	--	40.4	18.7	--	20.1	23.3	--	23.9	13.0
K	11.2	11.2	8.8	10.4	8.0	9.6	13.6	17.6	16.0
	4.4	5.2	1.8	3.6	0.0	3.6	6.7	6.1	4.9
Mg	16.0	18.4	14.4	15.6	15.2	15.2	14.4	25.6	15.2
	11.7	12.8	10.0	7.7	5.9	4.4	8.3	20.7	3.3
Mn	0.5	0.5	0.5	0.5	0.9	0.3	0.4	0.7	0.4
	0.3	0.2	0.1	0.2	0.5	0.2	0.2	0.5	0.2
OM%	2.2	2.6	1.5	1.8	2.4	1.5	1.9	3.8	1.4
	1.0	0.9	0.6	0.3	0.8	0.3	0.8	3.5	0.4
pH	4.7	4.1	4.3	4.8	4.2	4.2	4.9	4.0	4.0
	0.2	0.1	0.3	0.2	0.1	0.2	0.2	0.2	0.2
P	2.2	1.8	2.1	2.2	1.7	2.2	4.8	8.0	5.0
	0.9	0.6	0.5	0.7	0.4	0.3	2.7	5.7	2.2
TN	496.3	459.0	330.2	520.4	386.6	349.2	452.8	527.2	355.4
	108.5	39.6	107.3	35.5	107.9	62.9	87.6	262.6	84.4
MC%	17.1	19.0	18.5	15.4	18.4	18.8	15.1	18.5	17.9
	2.9	1.2	3.6	2.6	2.3	1.8	2.3	4.3	2.7
Zn	--	0.9	0.6	--	1.4	1.1	--	5.3	2.9
	--	0.5	0.2	--	1.2	1.1	--	6.3	4.9

Table A3.1., continued.

	9-YR-OLD PLANTATION								
	Control			Burned			PK-fertilized		
	S	F	SP	S	F	SP	S	F	SP
AR	66.1	58.2	93.6	126.9	47.6	229.3	93.2	151.5	261.1
	35.1	29.8	45.4	150.9	39.0	262.2	110.3	306.3	245.2
AL	79.2	136.0	102.4	47.2	57.6	36.6	59.2	38.4	45.6
	101.3	172.8	121.7	19.3	40.5	12.4	41.3	19.3	12.5
Ca	76.0	127.2	72.8	120.8	105.6	103.2	112.8	71.2	93.6
	62.3	120.5	44.4	44.3	36.3	55.7	45.4	23.7	23.9
Fe	--	31.0	27.9	--	31.7	13.3	--	32.2	19.8
	--	24.7	25.7	--	14.3	6.0	--	35.3	13.6
K	8.0	11.2	9.6	11.2	12.0	9.6	13.6	17.6	18.4
	2.8	7.2	2.2	1.8	4.0	2.2	8.3	4.6	13.6
Mg	16.0	16.8	15.2	22.4	27.2	17.6	20.8	13.6	15.2
	11.0	10.4	9.1	8.8	12.5	6.7	9.1	5.4	5.2
Mn	0.5	0.4	0.3	0.7	0.8	0.9	0.7	0.6	0.4
	0.3	0.1	0.1	0.5	0.4	1.1	0.7	0.4	0.2
OM%	2.7	2.6	2.0	2.8	2.8	1.6	3.3	2.6	2.2
	0.7	1.0	0.5	1.0	1.2	0.6	1.0	1.6	0.7
pH	4.7	4.1	4.2	4.6	4.1	4.3	4.4	3.9	3.9
	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.2	0.2
P	1.7	2.0	1.7	2.2	2.2	2.0	5.7	6.8	6.9
	0.5	0.2	0.3	0.4	0.4	0.5	2.8	3.1	0.9
TN	636.8	552.8	503.2	620.6	580.8	396.2	623.2	528.4	530.4
	108.6	118.4	169.2	155.8	219.4	129.1	120.1	214.7	173.2
MC%	16.9	19.2	24.4	13.1	19.5	19.5	16.9	19.3	24.2
	6.4	5.3	5.1	1.3	6.8	3.4	3.6	6.4	5.1
Zn	--	5.3	0.7	—	1.3	1.0	--	6.8	1.2
	--	2.0	0.1	--	1.0	0.4	--	8.9	1.2

Table A3.1., continued

	29-YR-OLD PLANTATION								
	Control			Burned			PK-fertilized		
	S	F	SP	S	F	SP	S	F	SP
AR	49.0	29.8	230.1	78.1	99.6	84.0	54.4	25.8	479.0
	19.5	25.1	324.9	46.4	82.0	33.3	48.7	15.7	554.3
AL	67.2	85.6	57.6	85.6	83.2	64.8	51.6	78.0	48.8
	40.9	48.2	30.6	20.7	31.9	35.6	16.1	16.2	15.6
Ca	32.0	32.0	32.8	25.6	25.4	38.4	112.0	61.6	50.4
	13.3	13.9	16.8	13.4	8.1	26.8	149.9	48.7	16.4
Fe	--	40.6	19.9	--	32.3	21.4	--	49.9	23.1
	--	21.0	11.2	--	12.0	10.9	--	25.7	12.5
K	5.6	8.0	5.8	4.8	9.6	6.4	15.2	21.6	12.8
	2.2	0.1	2.2	1.8	2.2	2.2	12.1	8.3	1.8
Mg	12.8	13.6	11.2	12.8	14.4	14.4	28.8	19.2	12.8
	5.2	5.4	3.3	5.2	2.2	6.1	33.8	12.5	3.3
Mn	0.2	0.5	0.2	0.2	0.4	0.1	0.4	0.6	0.3
	0.1	0.3	0.1	0.0	0.2	0.0	0.3	0.2	0.2
OM%	2.1	2.2	1.6	2.3	2.6	1.6	3.3	2.6	1.6
	0.7	0.8	0.4	0.5	0.9	0.3	2.7	1.3	0.2
pH	4.6	4.0	4.0	4.6	4.0	4.0	4.4	3.7	3.9
	0.3	0.1	0.2	0.1	0.1	0.1	0.4	0.2	0.3
P	2.1	1.0	1.5	2.0	1.3	2.0	5.9	11.8	8.6
	0.6	0.0	0.5	0.2	0.5	0.6	2.9	5.9	5.5
TN	577.3	417.2	384.4	677.0	428.2	394.4	729.4	481.8	416.6
	163.1	119.5	156.9	116.1	159.8	51.7	214.5	250.7	87.5
MC%	13.6	15.8	16.8	12.0	16.5	16.0	14.3	18.9	18.6
	1.4	2.7	4.7	1.2	4.4	1.6	2.8	6.3	4.5
Zn	--	0.6	0.7	--	1.0	0.9	--	0.8	0.8
	--	0.1	0.1	--	0.9	0.6	--	0.3	0.3

Table A3.1., continued

	29-YR-OLD PLANTATION		
	NPK FERTILIZED		
	SUMMER	FALL	SPRING
AR	18.4	6.5	44.9
	7.4	5.0	24.9
Al	22.4	20.8	20.0
	8.6	5.2	5.7
Ca	35.2	31.2	52.8
	15.6	17.3	18.6
Fe	--	13.1	6.1
	--	6.4	0.9
K	27.0	38.4	34.4
	10.9	14.6	13.7
Mg	8.6	8.0	7.2
	3.3	4.0	1.8
Mn	0.3	0.4	0.3
	0.0	0.2	0.1
OM%	1.6	1.4	1.3
	0.3	0.2	0.3
pH	5.0	4.5	4.9
	0.5	0.2	0.1
P	6.6	3.0	1.9
	4.8	2.6	0.6
TN	593.8	341.4	367.2
	75.6	62.6	98.5
MC%	9.7	10.2	14.3
	0.3	0.5	1.1
Zn	--	7.2	1.5
	--	3.6	1.1

APPENDIX 4

EXTRACTABLE P ANALYSIS

Introduction

In this section, P concentration changes after the 30-day incubation period are presented. This study was performed simultaneously with the N mineralization investigation to determine if some relationships between the two processes existed (Cole and Heil, 1981).

Double acid extractable soil P concentrations were measured before and after a 30-day incubation period in the field and laboratory. The lower ion exchange resin (extracted with KCl) and the drained water from the field and saturated laboratory cores, respectively, were included in the analysis. Details of the procedures used are described in the Methods section in the dissertation text, and in Appendix 1.

Results

During the summer, an interaction between plantation age and treatment was found ($p = 0.04$, Tables A4.1-A4.2). When plantation ages were compared within treatments, no differences were detected in the control and burned cores, although they tended to have slightly higher concentrations in the clearcut area than in the other areas. On the other hand, concentrations of P in the PK plots were at least 1.3 times as large in the 9- and 29-year-old stands ($p = 0.05$) than those found in the clearcut area (Table A4.1.).

Table A4.1 Summer soil inorganic P concentrations (mg P/kg) for the various treatments and plantations. Different letters within a column indicate significant differences ($p = 0.05$) from controls.

	PLANTATION AGES (yrs)		
Treatment	0	9	29
Control	5.4 a	3.2 a	4.2 a
Burned	6.9 a	5.0 a	5.0 a
PK	20.8 b	33.0 b	26.0 b

Table A4.2. Summer net P concentrations changes (mg P/kg-mo) for the various treatments and plantations. Different letters within a column indicate significant differences ($p = 0.05$) from controls.

	PLANTATION AGES (yrs)		
Treatment	0	5	29
Control	1.7 a	0.8 a	1.1 a
Burned	2.8 a	1.7 a	0.8 a
PK	-1.1 a	4.7 b	2.8 a

As expected, when treatments were compared within plantation age, in all cases PK plots had significantly higher ($p = 0.05$) concentrations which were at least 3 times larger than the control or burned plot levels.

When changes in P concentrations were determined before and after the incubation period, the burned plots had at least 1.7 times higher concentrations than the control plots in the clearcut and 9-year-old plantation (Table A4.2), and the PK plots had at least 2.7 higher rates in the 9- and 29-year-old stands. Negative values were observed in the PK plots from the clearcut area. No treatment values were statistically different from the controls except in the PK treated plots in the 9-year-old plantation.

During the fall, interactions between treatment and incubation method and between treatment and plantation age, were significant at the 0.0003 level.

When treatments were compared within incubation methods (Table A4.3), control and burned plots showed no significant differences in P concentrations, and changes after the incubation period were near 0 or negative (Table A4.4). On the other hand, P concentrations in the PK plots were at least 8 times larger than the other treatments, and relatively high increases in concentration after the incubation period were found in these plots; they were significantly different ($p = 0.05$) in the field and the saturated incubations when compared with the same incubation methods in the control plots. A relatively large portion of the P detected in the field incubated cores came from the lower ion exchange resin (see Appendix 1).

Table A4.3. Fall soil inorganic P concentrations (mg P/kg) for the various treatments and incubation methods (IC = initial conditions, F = field, U = unsaturated laboratory, and S = saturated laboratory cores). Different letters within a column indicate significant differences ($p = 0.05$) from controls.

	INCUBATION METHOD			
Treatment	IC	F	U	S
Control	2.3 a	1.9 a	2.0 a	2.4 a
Burned	2.4 a	2.3 a	2.7 a	3.4 a
PK	24.1 b	36.8 b	25.9 b	27.9 b

Table A4.4. Fall net P concentration changes (mg P/kg-mo) for the various treatments and incubation methods (IC = initial conditions, F = field, U = unsaturated laboratory, and S = saturated laboratory cores). Different letters within a column indicate significant differences (p = 0.05) from controls.

	INCUBATION METHOD		
Treatment	F	U	S
Control	-0.4 a	-0.3 a	0.1 a
Burned	-0.1 a	0.3 a	1.0 a
PK	12.7 b	1.7 a	3.7 b

When incubation methods were compared within treatments (Table A4.3) no effects were detected in the control and burned plots. On the other hand, the field and saturated cores from the PK fertilized plots tended to have higher concentrations of P than initial conditions or unsaturated cores, but only the field cores were significantly different ($p = 0.05$) from the initial condition cores.

Plantation age also had some effect on inorganic P concentrations, but only on those plots fertilized with PK (Table A4.5). Significantly higher ($p = 0.05$) concentrations were detected in the oldest stand and in the 9-year-old plantation when compared with the clearcut site. The 29-year-old stand also had significantly higher P levels that the 9-year-old site ($p = 0.05$).

When changes in P concentrations after the incubation period were investigated (Table A4.6), clearcut values tended to be negative, even in the PK fertilized plots. In the other areas values tended to increase and were especially high in the PK plots.

During the spring, the plantation age-treatment interaction was statistically significant ($p = 0.002$, Tables A4.7-A4.8). As in the fall, control and burned plots had similar P concentrations when they were compared among the different areas. But in the PK fertilized plots, the clearcut site had approximately half the concentrations observed on the other two areas ($p = 0.05$). No differences were observed between the 9-year-old and the 29-year-old plantations.

When changes in P concentrations after the incubation period were studied, in a majority of the cases values were negative or near 0 (Table A4.8). There was a decrease in P concentrations in the PK fertilized plots of the 9-year-old plantation, contrary to the results

Table A4.5. Fall soil inorganic P concentrations (mg P/kg) for the various plantation ages and treatments. Different letters within a column indicate significant differences ($p = 0.05$) from controls

	PLANTATION AGE (yrs)		
Treatment	0	5	29
Control	2.3 a	2.0 a	2.0 a
Burned	2.9 a	2.6 a	2.6 a
PK	17.1 b	22.4 b	46.3 b

Table A4.5. Fall net P concentration changes (mg P/kg-mo) for the various plantation ages and treatments. Different letters within a column indicate significant differences ($p = 0.05$) from controls.

	PLANTATION AGE (yrs)		
Treatment	0	9	29
Control	-0.1 a	0.2 a	-0.6 a
Burned	0.7 a	0.5 a	0.0 a
PK	-2.4 a	7.3 b	13.3 b

Table A4.7. Spring soil inorganic P concentrations (mg P/kg) for the various plantation ages and treatments. Different letters within a column indicate significant differences ($p = 0.05$) from controls.

	PLANTATION AGE (yrs)		
Treatment	0	9	29
Control	3.3 a	2.1 a	2.1 a
Burned	3.5 a	2.9 a	2.3 a
PK	8.0 b	16.3 b	17.6 b

Table A4.8. Spring net P concentration changes (mg P/kg-mo) for the various plantation ages and treatments. Different letters within a column indicate significant differences ($p = 0.05$) from controls.

	PLANTATION AGE (yrs)		
Treatment	0	9	29
Control	0.4 a	0.0 a	-0.3 a
Burned	-0.2 a	-0.4 a	-0.2 a
PK	-0.7 a	-4.6 b	2.7 b

observed in the 29-year-old stand. In this later site, almost 3 mg P/kg-mo were produced.

In the following sections, results comparing the different seasons within each of the three sites will be presented.

In the clearcut area, a 3-way interaction between season, treatment, and incubation method was significant ($p = 0.04$, Tables A4.9-A4.10). When seasons were studied within each of the incubation methods and treatments, inorganic P concentrations decreased in the fall and spring to about half the summer values. In spring, concentrations tended to increase somewhat from fall levels.

The above tendencies were hidden in the PK fertilized plots as a result of the early October fertilization. P concentrations in the fall were statistically similar to those analyzed in the summer, although much higher concentrations were expected after two applications of fertilizer in the same year. A strong decrease, to about half of the fall concentrations, was observed in spring.

When changes in P concentration after the incubation period (Table A4.10), a decrease in concentrations at the end of the incubation period was observed in the fall and spring, especially in the saturated cores from the burned plots (these were statistically different, $p = 0.05$, when compared to control rates). In the PK fertilized treatment, negative values were observed in the summer (especially in the unsaturated cores). In the fall, the field incubated cores showed a statistically significant ($p = 0.05$) increase in amounts after the incubation period (approx. 4.0 mg P/kg-mo) when compared with summer or spring rates. In the same period, the

Table A4.9 Seasonal soil inorganic P concentrations (mg P/kg) in the clearcut area for the various incubation methods (IC = initial conditions, F = field, U = unsaturated laboratory, and S = saturated laboratory cores) and treatments. Different letters within a column indicate significant differences (prob. level 0.05) from summer.

	CONTROL INCUBATION METHOD			
Season	IC	F	U	S
Summer	4.2 a	5.2 a	6.3 a	6.1 a
Fall	2.4 a	2.3 a	2.1 b	2.5 b
Spring	2.9 a	2.9 a	3.0 a	4.4 a
	BURNED INCUBATION METHOD			
Season	IC	F	U	S
Summer	4.9 a	6.7 a	6.2 a	10.0 a
Fall	2.4 a	2.6 b	3.3 a	3.5 b
Spring	3.7 a	3.6 a	3.2 a	3.7 b
	PK FERTILIZED INCUBATION METHOD			
Season	IC	F	U	S
Summer	21.6 a	21.0 a	17.6 a	22.9 a
Fall	19.9 a	23.0 a	13.6 b	12.9 b
Spring	9.5 b	7.6 b	7.2 b	9.7 b

Table A4-10. Seasonal net P concentration changes (mg P/Kg-mo) in the clearcut area for the various incubation methods (F = field, U = unsaturated laboratory, and S = saturated laboratory cores) treatments. Different letters within a column indicate significant differences (prob level 0.05) from summer.

	CONTROL INCUBATION METHOD		
Season	F	U	S
Summer	1.0 a	2.1 a	2.0 a
Fall	-0.2 a	-0.3 a	0.1 a
Spring	-0.1 a	0.0 a	1.4 a
	BURNED INCUBATION METHOD		
Seasons	F	U	S
Summer	1.9 a	1.4 a	5.2 a
Fall	0.2 a	0.9 a	1.1 b
Spring	-0.1 a	-0.5 a	0.0 b
	PK FERTILIZED INCUBATION METHOD		
Season	F	U	S
Summer	-0.5 a	-4.0 a	1.2 a
Fall	3.9 b	-5.2 a	-6.0 b
Spring	-0.9 a	-1.3 a	0.2 a

unsaturated and saturated cores had high negative values which were significant ($p = 0.05$) in the saturated cores when compared with the summer and spring rates.

In the 9-year-old plantation, a highly significant ($p = 0.0001$) interaction between treatment and season was observed (Tables A4.11-A4.12). When seasons were compared within each of the treatments, no statistical differences were detected in the control or burned plots, although P concentrations tended to drop in the fall and spring (Table A4.11). PK fertilized plots showed a decrease in concentrations (more than 50% over the year) with fall and spring values significantly lower from summer values ($p = 0.05$).

When changes in P concentrations after the incubation period were calculated (Table A4.12), a relatively strong increase was observed in the PK plots in the summer and fall, but drastically dropped in the spring ($p = 0.05$), from 7.3 mg P/kg-mo to -4.6 mg P/kg-mo. Rates in the control and burned plots, although non-statistically different from summer values, also tended to decrease with season to negative values in spring. In the 29-year-old plantation, the treatment-season interaction was also significant ($p = 0.003$). Average P concentrations and rates are shown in Tables A4.13 and A4.14.

When the different seasons were compared, statistically similar P concentrations were found for the control and burned plots, although they tended to drop by half in the fall and spring from summer values (Table A4.13). On the other hand, in the PK fertilized plots, concentrations almost doubled in the fall ($p = 0.05$) when compared with summer concentrations following the second application of PK fertilizer in October, but decreased 2.6 times in the spring from fall levels ($p = 0.05$).

Table A4.11. Seasonal soil inorganic P concentrations (mg P/kg) in the 9-yr-old plantation for the various treatments. Different letters within a column indicate significant differences ($p = 0.05$) from summer

	TREATMENT		
Season	Control	Burned	PK fertilized
Summer	3.2 a	5.0 a	33.0 a
Fall	2.0 a	2.5 a	22.4 b
Spring	2.1 a	2.9 a	16.4 b

Table A4.12. Seasonal net P concentration changes (mg P/kg-mo) in the 9-yr-old plantation for the various treatments. Different letters within a column indicate significant differences ($p = 0.05$) from summer.

	TREATMENT		
Season	Control	Burned	PK fertilized
Summer	0.8 a	1.7 a	4.7 a
Fall	0.2 a	0.5 a	7.3 b
Spring	0.0 a	-0.4 a	-4.6 b

Table A4.13. Seasonal soil inorganic P concentrations (mg P/kg) in the 29-yr-old plantation for the various treatments. Different letters within a column indicate significant differences ($p = 0.05$) from summer.

	TREATMENT			
Season	Control	Burned	PK fertilized	NPK fertilized
Summer	4.2 a	5.0 a	26.0 a	12.7 a
Fall	2.0 a	2.6 a	46.3 b	5.3 b
Spring	2.1 a	2.3 a	17.6 b	3.1 b

Table A4.14. Seasonal net P concentration changes (mg P/kg-mo) in the 29-yr-old plantation for the various treatments. Different letters within a column indicate significant differences ($p = 0.05$) from summer.

	TREATMENT			
Season	Control	Burned	PK fertilized	NPK fertilized
Summer	1.1 a	0.6 a	2.8 a	4.2 a
Fall	-0.6 a	0.1 a	13.3 b	0.4 b
Spring	-0.3 a	-0.2 a	2.7 a	-2.4 b

The P concentration after the incubation period increased in the PK fertilization in the fall after the second application of P (Table A4.14). Rates quadrupled in the fall but decreased again during the spring incubations to concentrations similar to those found in the summer. In control and burned plots, changes in P concentrations after the incubation period were small over the seasons and, in general, they were low or even negative, especially in the spring (Table A4.14).

When the NPK treatment was added to the statistical analysis of P concentration changes over the incubation period for the 29-year-old plantation, the following results were obtained (see Tables A4.13-A4.14):

1) When comparing the treatments within the seasons, the NPK fertilized plots had lower inorganic P concentrations than the PK plots ($p = 0.05$), but were at least 2 times higher than the control and burned plots in the summer and fall seasons (although only in the summer they were statistically different from control at $p = 0.05$). In the spring, the NPK treated cores had similar concentrations as the control cores.
2) A significant decrease (about 2.4 times) in P concentrations was observed in the fall and spring seasons ($p = 0.05$) when compared with the summer. Although the site was fertilized with more P in August 1983, only less than 4 months before the fall sampling was conducted, no increase in P concentration was observed.
3) When changes in P concentration after the incubation period were studied in the summer, the NPK plots had higher concentration changes than the PK (4.2 mg P/kg-mo in the NPK, to 2.8 mg P/kg-mo

in the PK, $p = 0.05$). But in the fall and spring, concentrations changes dropped considerably to near 0 or less, in the spring (Table A4.14). The net changes in concentration after the incubation period in the PK plots were 33 times and 6 times larger in the fall and spring, respectively, when compared with the NPK rates.

Discussion

Low availability of P (as well as of N) is a major factor regulating plant distribution and productivity of both natural and managed ecosystems in Florida. For example, moderate to large volume gains have been observed in semimature slash pine plantations after fertilization with P and often without N (Kaufman et al., 1977, Fisher and Garbett, 1980), depending on the soil characteristics of the site.

In addition to possible direct effects on plant nutrient uptake and growth, addition of fertilizers may change activity of microbial processes in the soil. Adequate availability of P has been shown to be an important factor controlling ammonification, nitrification, and biological N_2 fixation (Cole and Heil, 1981) thus contributing to the proper functioning of the entire ecosystem.

In highly weathered sandy soils, like those found in northern Florida, availability of P is largely controlled by the release of inorganic P from organically bound P through the microbial mineralization process (Harrison, 1982). Once mineralized, inorganic P may be leached, absorbed by the vegetation or immobilized in microbial biomass, become bound to the anion exchange sites of the mineral soil or organic matter, or may be complexed with Al or Fe under acid conditions.

In the present investigation, different results were obtained depending on treatment, plantation age, and season. Incubation method had little effect except during the fall.

During the summer (Table A4.1-A4.2), the slightly higher P concentrations in the non-P fertilized clearcut plots when compared to the other two areas, may have been a result of the recent clearcutting. On the other hand, the 5-year-old plantation had the lowest initial P concentrations with net changes in P concentration at the end of the incubation period similar to those found in the oldest stand. These low initial concentrations may have been related to the more active uptake of this nutrient by the vegetation of this site (Gholz, Fisher, and Pritchett, in press).

When PK treated plots were compared among plantation ages and other treatments, different tendencies were observed. Net changes in P concentration after the incubation period in the clearcut site were at least 3 mg P/kg-mo lower than those in the other treatments in the same plot, and at least 4 mg P/kg-mo lower than in other plantations. It is difficult to explain why these results occurred, except to speculate that the increases in P due to the recent disturbance in the clearcut area were not sufficient to stimulate microbial immobilization, but when additional P was added to the area through fertilization, microbial activity was effectively increased. Also, increased availability of K in the PK fertilized plots may have had some effect. Similar tendencies were observed in the fall and spring (Table A4.3-A4.4, A4.7-A4.8). Again, the control and burned plots in the clearcut site had higher average concentrations and they tended to increase during the incubation period when compared with the other two plantations, but

differences were less evident. In the PK treated plots, fall concentrations and rates were half or less, respectively, in the clearcut area than in the other sites. Spring concentrations were also about 2 times less, but net changes in P concentrations were lower only when compared with the 29-year-old site.

Burned plots showed slightly higher concentrations before and after the incubation period than control plots in all areas. Highest values were obtained in the summer, 3 months after the fire. This indicates that burning released P, although effects seem to be temporary and small. Regular burning of the site, then, may facilitate and increase availability of P for vegetation growth, and would accelerate P release from the litter layer. In the clearcut site, however, burning may be potentially detrimental as little vegetation was present during the first year to take advantage of any increase, so P losses through leaching are expected to increase. Analysis of the bottom ion exchange resin (Appendix 1) indicates that the amount of P trapped by the resin increase in the burned plots but only represented about 10% of the total extractable P detected for the cores.

Phosphorus fertilization increased extractable P in all seasons, as expected, but effects on P concentration changes after the incubation period varied among locations and seasons. In general, P concentration increased in the 9- and 29-year-old plantations during the summer and fall, but decreased in the clearcut in all seasons and in the 9-year-old plantation in the spring, after the cores were incubated.

Finally, when concentrations were studied among seasons, a strong decline was observed in the fall and spring (Table A4.9-A4.14).

Negative values in the spring after the 30-day incubation may have been the product of microbial growth increase during this period of ideal weather. Also, large decreases in concentrations were found in the P fertilized plots, especially in the clearcut site and in the spring. In the NPK site, levels dropped almost to control concentrations in the fall, about 4 months after the latest P addition. These results suggest that, either very high uptake rates were occurring, or that P losses through complexation with Al and Fe, or leaching were high. Losses would be expected to be higher in the disturbed area, as little or no vegetation was present, and more water would percolate through the surface soil. Results from the lower ion exchange resin analysis indicate that 50 to 75% of the total extractable P in the P fertilized plots were extracted from the resin. This suggests that the potential for leaching losses is very high in fertilized sites (Appendix 1).

No remarkable tendencies were observed among incubation methods except in the fall (Table A4.3-A4.4). Higher concentrations occurred in the field and saturated incubated cores. As mentioned, in the PK fertilized plots, relatively large quantities of P were extracted from the ion exchange resin (see Appendix 1), contributing to the elevated values in the cores from this treatment. This may have been a result of drying and wetting cycles releasing labile organic P, or to increased P solubility after several soil solution washes through the cores. The increase of P in the saturated cores may also have been due to an increase in the solubility of P from absorption-desorption sites, in addition to mineralization processes (Reddy and Rao, 1983). Also, Reddy and Patrick (1983) indicated that such an increase in P

solubility under anaerobic conditions may be due to the reduction of certain inorganic forms of P, especially Fe-P forms, and to an increase solubility of organic matter which helps release P.

In the majority of the cases, P concentrations before and after the incubation period were not significantly different when incubation methods were compared within treatment, suggesting that other factors besides temperature, initial inorganic P concentrations, and soil moisture content were regulating P processes. No significant increases in extractable P were detected in the laboratory incubated cores when compared with the field incubated cores in the fall and spring (see Appendix 2) as was the case for ammonium-N, which suggests that availability of P may not be strongly mediated by soil microorganisms.

P is strongly immobilized in the litter layer from these slash pine plantations (Gholz, Perry, Cropper, and Hendry, in press). P contents in decaying needles increase 0-90% over the original amount after 24 months, with needles in the older stands showing greater accumulations. Throughfall concentrations can barely account for the observed increases, so that lower layers in the forest floor and/or mineral soil must be the sources of mineralized P available for plant uptake.

Although relatively small net changes in P concentrations after the incubation period were found, which mainly occurred in the summer, there may still be sufficient amounts of P to satisfy plant uptake rates. Net P concentrations increased between 0.8-1.1 (0.9-1.2) in the control, 0.6-1.7 (0.7-1.9) in the burned, and 2.8-5.0 mg P/kg-mo

(3.1-5.5 kg/ha-mo) in the fertilized plots collected in the summer from the 9- or 29-year-old plantation (Table A4.2).

According to Gholz, Fisher, and Pritchett (in press), uptake of P by vegetation in the unfertilized stands ranged from 3.5-1.9 kg P/ha-yr in an 8- and 26-year-old plantations, respectively. If I assume 4-6 months in which net amounts of organically bound P is released through microbial activity, and if the double acid extractable P actually correlates well with plant uptake (as has been suggested by Thomas and Peaslee, 1973, and Ballard and Pritchett, 1975), then even control plots appear to supply sufficient amounts of P (4 to 6 kg P/ha-yr) for vegetation uptake (Table A4.15). But the 9-year-old plantation, which is more dependent on availability of nutrients from the soil than on internal recycling (Gholz, Fisher, and Pritchett, in press) may, in some instances, be P limited. On the other hand, the supplying capacity observed on the control plots, appears to be sufficient to sustain uptake rates of the older stand (3.0 kg P/ha-yr) if no internal recycling occurred. Internal recycling is high, and P concentrations in tissue are low (Gholz, Fisher, and Pritchett in press) in these stands, which suggests that all the extractable P may not be available for the vegetation (less than 10% of the total extractable P detected, was found in the bottom resin), or that the net increases in concentration at the end of the incubation period are not always as high as those observed in this investigation. If the site is burned or fertilized, additional P may become available (Table A4.15), but increases seem to be temporary unless treatments are repeated regularly (if large amounts of P are applied at once through fertilization, potential leaching losses may

Table A4.15. Summer calculated net P concentration changes (kg/ha-yr) in the 9- and 29-yr-old plantations for the various treatments assuming either 4 or 6 months of microbial activity per year.

	TREATMENTS					
	Control		Burned		PK fertilized	
	4 months	6	4 months	6	4 months	6
min.	3.6	5.4	2.8	4.2	12.4	18.6
max.	4.6	7.2	7.6	11.4	22.0	33.0
x	4.2	6.2	6.2	7.8	17.2	25.8

be high). As mentioned ion exchange resin extractions indicated that as much as 75% of the total P detected in the P fertilized cores was trapped by the resin.

Figure A4-1 gives the best current estimates P fluxes for the 29-year-old plantation when not fertilized with P. Similar values occur in the other two sites, except in the clearcut area where high leaching losses are expected as little or no vegetation uptake occurred.

It is important to observe that the uptake values obtained by Gholz, Fisher and Pritchett (in press) may represent rates for vegetation already adapted to low concentrations of nutrients. According to Chapin (1983), major adaptations of some vegetation to low nutrient availability include slow growth rates and reduced annual nutrient requirements. In Chapin's experiments, when low-nutrient-adapted tree species were supplied with P, they had a lower capacity for P absorption and were less efficient in producing biomass, i.e. they tended to store the extra P. Although some of these characteristics are largely genetic in nature, some phenotypic flexibility may exist in species, such as slash pine, where they may react selectively depending on the nutrient availability in the soil

Conclusions

The following conclusions can be drawn from the results obtained in this experiment:

1) Extractable P concentrations before and after the incubation period were similar in all plantation ages in the non-P fertilized plots.
2) Burning increased P concentrations but increases were small and temporary.

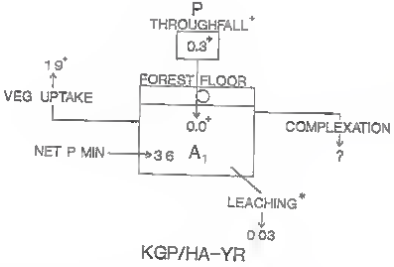


Figure A4.1. Estimated phosphorus fluxes (kg P/ha-yr) in an unfertilized 29-yr-old slash pine plantation (*Morris and Pritchett, 1982, and **Gholz, Fisher, and Pritchett, in press).

3) Phosphorus fertilization increased availability of double acid extractable P, as expected, but also increased the amount of P trapped in the bottom resin to as much as 75% of the total P detected in the cores.

Net P increases were higher in the 9- and 29-year-old plantations, although the opposite occurred in the recent clearcut site.

4) Phosphorus concentrations in the PK plots dropped very fast after the fertilization, especially in the clearcut area, which suggests that leaching losses were high. If this is the case, small amounts of P at a time must be added to the soil to avoid such losses.

5) Little differences in P concentrations before and after the incubation period were observed between incubation methods, suggesting that soil aeration and moisture content apparently did not have a strong effect.

6) In the fall and spring, P concentrations before and after the incubation period decreased. Interestingly, only a small increase was observed in the laboratory incubated cores when compared with the field incubated cores which suggests that other factors besides temperature are controlling this process. A relatively large decrease in P concentration after the incubation period was observed in the spring and especially high in the PK fertilized plots.

7) Net increases in extractable P after the incubation period are apparently sufficient to satisfy P uptake rates of the vegetation in the 9-year-old and 29-year-old plantations, although P stress may still be possible in the 9-year-old plantation, as vegetation

is less dependant on internal recycling and growth requirements are greater than older plantations.

8) In the non-fertilized plots, bottom resin and drained water analyses indicated that P present in soil solution was low (less than 10% of the total P detected in the cores, Appendix I). This suggests that mass flow transport of P to the roots may be a limiting factor in vegetation uptake.

APPENDIX 5

EFFECTS OF AIR-DRYING AND REWETTING
A MIXED-BED ION EXCHANGE RESIN

Introduction

Ion exchange resins (IEN) have recently been used to assess forest soil nitrogen (N) availability (Binkley and Matsen, 1983) and N leaching (Schnabel, 1983) with very encouraging results. In addition, P extraction from the anion portion of the resin has been used as P availability index (Amer et al., 1955, Olsen and Sommers, 1982). This method offers the advantage of being sensitive to on site conditions, when used in field experiments, without producing pH changes or other chemical alterations in the soil.

A key factor in their effective used is the quantitative and reproducible extraction of N ions (NH_4, NO_3) from the resin complex. Several tests have been performed on the N extraction efficiency of KCl (Schnabel, 1983, Hart and Binkley, 1984) and on the effect of time on the amount of N retained by the resin (Schnabel, 1983, Binkley, in press). These studies have concluded that extraction efficiencies for the ammonium- and nitrate-N are high (80 to 90%) and that no transformations occur even after 12 weeks of storage.

On the other hand, no studies have been made on the impact of drying and wetting cycles, a potentially frequent occurrence in the surface of forest soils, and on the ability of the resin to capture and/or maintain N species. It is known that physical damage does

occur when the resin is dehydrated (D. W. Tamaki, Sybron Chem Div., pers. comm., 1983).

The purpose of the present investigation was to study the effects of moisture losses and rewetting cycles on the IER properties.

Methods

A self-indicating, certified research grade, mixed-bed IER (Rexyn i-300, Fisher Scientific Co.) was used. Properties are presented in Table 5. The experiment was divided in two parts.

A) Ten flasks each containing 9 g (wet weight) of the IER were allowed to dry to different moisture contents (ranging from about 30 to 55%, by weight), rewetted and air-dried again. After the second cycle, 30 ml of ammonium nitrate (5.1 mg/ml=2.8 mg N/ml) were added to 9 g resin and mixed for 1 hr (a very high concentration were added to test the ability of the resin to retain high levels of N after wetting-drying cycles). The solution was then filtered with a Whatman # 42 filter paper and analyzed for ammonium-N using the steam distillation procedure (Bremner, 1965) and nitrate-N using the Technicon Autoanalyzer II (Technicon Industrial Systems, 1978).

This part tested whether or not the ability of the resin to trap added NH_4 and NO_3 is affected by prior drying-wetting cycles.

B) Ten flasks each with 9 g (wet weight) of the IER were mixed with 30 ml of ammonium nitrate (5.4 mg/ml=1.8 mg N/ml) for 1 hr. Excess solution was drained and discarded (it was assumed all the ammonium nitrate was trapped by the resin). The resin was then allowed to dry to different moisture contents ranging from 25 to 60%, by weight. Resin was rewetted by pouring 30 ml of deionized water into the resin sitting in a funnel with a Whatman #42 filter paper. Excess water was then

analyzed in the steam distillation to determine ammonium- and nitrate-N. Finally, the washed resin was air dried again and rewetted for a second time as before. Resin nitrogen was not extracted with KCl at the end of the experiment.

This part tested whether or not added ammonium and nitrate was released after a cycle of drying and wetting.

Results and Discussion

Data obtained from the first part of the experiment, i.e. air drying the resin without N, are shown in Table A5.1. In general, the drier the resin the less ammonium and nitrate was trapped (more was detected in the filtrate) until a resin weight of approximately 5 g was reached. At this point, N concentrations in the filtrate dropped, but began rising again as the resin lost more water.

These results appear to indicate that some of the exchange sites of the resin were destroyed by the treatment, but when a certain moisture content was reached some of the ammonium and nitrate ions may have been absorbed by the dried beads. This suggests that rather than a chemical interaction with the ion exchange sites, ions were physically trapped inside the beads. As the resin got drier, more exchange sites were destroyed, but no more available space inside the bead was created, so that the concentrations of nitrogen increased again.

In addition, it was found that the controls produced some contamination which led to overestimation of the ammonium-N in steam distillation procedure. This interference may have been due to the presence of the quarternary amide, which forms part of the cation group of the resin, as it reacted with the magnisium oxide.

Table A5.I. Resin weights after the first (I) and second (II) air-drying cycles, and the concentrations of ammonium- and nitrate-N in the filtrate solution of the added ammonium nitrate (not trapped by resin).

I	II	NH_4-N	NO_3-N
---- g ----		------ mg/l ------	
9.0*	9.0	9.3	0.0
9.0*	9.0	8.7	0.0
8.9	8.9	8.3	0.7
8.6	8.8	9.6	0.5
8.0	8.5	11.2	0.8
8.0	8.4	19.4	1.3
7.0	6.4	17.6	1.6
6.3	5.9	2.4	0.9
6.2	5.9	4.2	0.4
5.6	5.3	10.4	0.8
5.5	5.4	9.6	1.3

*= controls, no N added, not air dried.

Results from Part B are presented in Table A5.2. After the first cycle there was an obvious increase in the nitrate-N released by the resin as it became drier. After the second cycle, this tendency was not observed although more nitrate-N was detected. Part of this nitrate-N may have been released from the anion exchange sites as a result of a concentration difference between the deionized water and the resin beads. Very little of the ammonium-N was released. Again some contamination was observed in the controls.

Conclusions

There is an indication that when the total moisture content of the resin is below 60%, resin ion exchange properties are affected. Higher concentrations of N were detected in the filtrate solutions after the drying and wetting cycles, suggesting that some N may not be trapped, or once N is in the resin, it may be released, (especially in the case of nitrate).

Under field conditions the resin is not normally expected to lose high amounts of moisture unless it is placed uncovered near the surface, or if the soil drastically dries for long periods of time. In addition, the amounts of N not trapped or released by the resin after the treatment, were very low relative to the high concentrations of N added to the resin. In the field, much lower concentrations usually occur, so that if some ion exchange sites of the resin are damaged, there should still be adequate sites available to capture and retain N in the soil solution

Table A5.2. Resin weights and ammonium- and nitrate-N concentrations in the deionized water wash after the first (I) and second (II) air-drying cycles.

I			II		
NW	NH_4-N	NO_3-N	NW	NH_4-N	NO_3-N
	------- mg/l --------		g	-------- mg/l -------	
6.7*	8.1	0.7	6.0	8.4	0.4
6.2*	7.8	0.5	6.5	8.7	0.5
7.4	1.1	0.5	8.7	6.0	5.2
7.1	1.1	1.1	8.3	5.6	4.1
6.3	4.2	3.6	6.9	5.3	4.9
5.9	4.6	3.8	6.4	6.3	4.1
5.3	7.4	4.7	6.0	6.0	3.8
5.1	7.4	4.9	5.6	6.3	3.8
5.0	6.3	4.9	5.6	6.7	4.2
4.9	6.3	5.2	4.9	6.3	3.5
4.9	7.0	5.1	4.8	7.7	6.3

*= controls, air-dryed, no N added.

APPENDIX C

CALIBRATION CURVE ON THE ION EXCHANGE RESIN

Introduction

An interference was found when ammonium-N extracted from a mixed-bead ion exchange resin (IER) was analyzed with the Technicon Autoanalyzer II. When concentrations of ammonium-N were low, color did not develop. It was found that by changing the concentration of sodium hypochloride from 6 to 9 ml/100 ml and sodium nitroprusside from 0.30 to 0.25 g/1000 ml in the Technicon procedure, and by diluting the sample, ammonium-N could be detected.

The purpose of this section is to describe the calibration a relationship between the amount of ammonium-N detected by the Technicon and that actually added to the IER. This relationship was later used to determine the concentration of ammonium-N trapped in the resin coming from the field incubated cores.

Methods

Two flasks each containing an equivalent of 2 g of air dry IER were mixed for 1 hr with 50 ml of a solution containing several concentrations of ammonium chloride (0-22 mg/l). After mixing, the solution was filtered with a Whatman #42 filter paper. The drained water was discarded assuming that all the N was trapped by the IER.

The IER with the added N was air dried for 5 days and then mixed with 50 ml of a 2N KCl solution for 1 hr. The mixture was filtered as before and analyzed with the modified Technicon procedure. Before the

analysis, the samples were diluted 2.5, 5 and 41 times. Levels of ammonium-N extracted from the IER were compared with the actual amount added.

Results

Results obtained from this experiment are shown in Fig. A6.1. In all dilution cases (e.g. 2.5, 5, and 41 times), the relationship between the ammonium-N levels extracted from the IER and the actual N amounts added were linear and with very high r^2's. The equations were

$$y_{2.5} = 0.156 + 0.320\ x;\ r^2 = 0.997$$

$$y_{5} = 0.167 + 0.525\ x;\ r^2 = 0.994$$

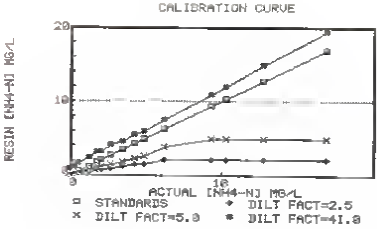
$$y_{41} = 0.951 + 1.077\ x,\ r^2 = 0.997$$

where

y = ammonium-N concentration extracted from the IER, and

x = ammonium-N concentration actually added to the IER

For the 2.5 and 5 times dilution factors, N extracted from the IER was lower than the amount added, but when sample was diluted 41 times, N extracted appear to be higher than the amounts added.



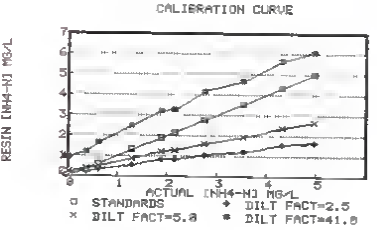


Figure A6.1 Relationship between the concentrations of ammonium-N extracted from the ion exchange resin to that actually added to the resin as detected by the modified Technicon Autoanalyzer II procedure. Samples were diluted 2.5, 5, and 41 times

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy

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